ASSESSMENT AND IMPROVEMENT OF SUSTAINABILITY EDUCATION IN CIVIL AND ENVIRONMENTAL ENGINEERING

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
August 2013

ASSESSMENT AND IMPROVEMENT OF SUSTAINABILITY EDUCATION IN CIVIL AND ENVIRONMENTAL ENGINEERING

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This work is dedicated to my loving husband who has selflessly supported me in all of my personal and professional endeavors.

ACKNOWLEDGEMENTS

Foremost, I would like to thank my advisor, Dr. Michael Rodgers for his support during my time at Georgia Tech. He has been an exceptional mentor who has encouraged me to develop expertise in unconventional, interdisciplinary research areas. Always a pleasure to work with, his honest and insightful advice has been indispensable.

In addition to my advisor, I would also like to thank my committee members. Drs. Nelson Baker, Randall Guensler, Donna Llewellyn, James Mulholland, Caroline Noyes, and Kari Watkins have provided valuable input that has greatly improved this research project. I would especially like to thank Dr. Noyes for her countless hours of guidance in the development and analysis of assessment methods.

Of course, this project would not have been possible without all of my undergraduate participants and graduate student collaborators. Special thanks to the students enrolled in Capstone Design and Civil Engineering Systems between Fall 2011 and Fall 2012. Much of this work could not have been conducted without the help of many of my colleagues, including Elise Barella, Alexandra Coso, Franklin Gbologah, Malek Hajaya, Teresa Misiti, Joshua Pelkey, Alex Samoylov, Ulas Tezel, and Tom Wall.

I would also like to thank my family and friends who have encouraged me over the years. My husband, Joshua Pelkey, has brought great happiness and balance to my life. Also, I would not have succeeded without my parents, David and Ann Marie Watson, who have always modeled for me the virtues of dedication and sacrifice. Finally, my “sisters” Amanda Hobson, Carolyn Bone, and Audrey Bone have been constant sources of support and entertainment.

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NOMENCLATURE

$\Delta_{post\text{-}pre}$	Difference in post and preliminary scores
$\pi_{6\text{-}7}$	Proportion of students providing a response of 6-7
χ^2	Chi-Square Statistic
$A_{D,i}$	Amount of Disposal Entry *i*
$A_{P,i}$	Amount of Production Entry *i*
$A_{U,i}$	Amount of Use Entry *i*
ABET	Accreditation Board for Engineering and Technology
AC	Abstract Conceptualization
AE	Active Experimentation
ASCE	American Society of Civil Engineers
CE	Concrete Experience
CivE	Civil Engineering
CEE	Civil and Environmental Engineering
Cmap	Concept map
DBER	Discipline-Based Education Research
DDT	Dichlorodiphenyltrichloroethane
DPSIR	Driving forces, Pressures, States, Impacts, Responses
DV	Dependent Variable
E_i	Earned points for criterion *i*
Econ	Economy
EIA	Environmental Impact Assessment
ELT	Experiential Learning Theory

Engr	Engineering
Engr Ed	Engineering Education
Env	Environmental
EnvE	Environmental Engineering Student
F	*F*-Distribution Variable
Georgia Tech	Georgia Institute of Technology
GLM	General Linear Model
GSE	Green Science and Engineering
Georgia Tech	Georgia Tech Seminar
HH	Highest Hierarchy
$I_{D,i}$	Eco-Indicator for Disposal Entry *i*
$I_{P,i}$	Eco-Indicator for Production Entry *i*
$I_{U,i}$	Eco-Indicator for Use Entry *i*
IRB	Institutional Review Board
ISO	International Organization for Standardization
IV	Independent Variable
LCA	Life Cycle Analysis
LEED	Leadership in Energy and Environmental Design
M	Mean
M_{earn}	Mean Earned Points
M_{pot}	Mean Potential Points
MET	Materials, Energy, Toxicity
n	Sample Size
N/A	Not Applicable

NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NatRes	Natural Resources
NC	Number of Concepts
NCL	Number of Cross-Links
NIL	Number of Interlinks
NRC	National Research Council
NSF	National Science Foundation
p	Level of Significance
$P_{D,i}$	Eco-points for Disposal Entry *i*
$P_{D,total}$	Total Disposal Eco-Points
P_i	Potential points for criterion *i*
$P_{P,i}$	Eco-points for Production Entry *i*
$P_{P,total}$	Total Production Eco-Points
$P_{U,i}$	Eco-points for Use Entry *i*
$P_{U,total}$	Total Use Eco-Points
PCB	Polychlorinated biphenyl
PSR	Pressures, States, Responses
RFQ	Request for Qualifications
R^2	Multiple Correlation Coefficient
RO	Reflective Observation
S_{ECO}	Eco-Score
SD	Standard Deviation
SD	Sustainable Development

SD_{score}	Sustainable Design Index (M_{pot} – M_{earn})
SOQ	Statement of Qualifications
SPSS	Statistical Package for the Social Sciences
SSE	Sustainability Science and Engineering
Stkhldrs	Stakeholders
STAUNCH®	Sustainability Tool for Auditing Universities Curricula Holistically
t	Students-*t* Variable
Tech	Technology
UK	United Kingdom
UN	United Nations
UNCSD	United Nations Conference on Sustainable Development
US	United States
UBC	University of British Columbia
VIP	Vertically-Integrated Project

SUMMARY

Sustainable development through sustainable engineering is a promising strategy for combating unsustainable patterns of population growth, resource consumption, and environmental degradation. For sustainable engineering to alleviate global problems, however, improvements in undergraduate education are required to equip students with the knowledge and skills needed to engage in sustainable design. Consequently, the goal of this dissertation is to assess and improve sustainability education in civil and environmental engineering (CEE) at the Georgia Institute of Technology (Georgia Tech). Three phases of inquiry were conducted to (1) examine the current status of CEE sustainability education, (2) use assessment results to develop a pedagogically-innovative sustainability module, and (3) investigate the impacts of implementing the module into select CEE courses on student learning.

In the first phase of research, both curricular and student knowledge assessments were completed to benchmark the current quality of CEE sustainability education. Both student surveys and the Sustainability Tool for Assessing Universities' Curricula Holistically (STAUNCH®) concurred that integration of sustainability into the curriculum was incomplete and favored the environmental dimension. In addition, CEE seniors' conceptual understanding of sustainability, based on concept map and student survey results, were found to be generally correct, although limited in comprehensiveness, connectedness, and balance. Finally, examination of capstone project reports developed between 2002 and 2011, analyzed using the novel Sustainable Design Rubric, suggested that students primarily addressed social sustainable design criteria while "meeting the expectations" of project sponsors and course instructors. Preliminary assessments support the potential for improvement of both curricular and student knowledge quality.

The second portion of this research centered on development of a sustainability module for improving CEE student learning about sustainability. Based on the results of curricular and student knowledge assessments, the module was intentionally designed to enrich students' knowledge by aiding them in developing a comprehensive, connected, and balanced understanding of sustainability before providing them with opportunities to practice sustainable design skills. As per best practices in teaching and learning, activities were sequenced according to Kolb's learning cycle and designed to incorporate several active pedagogies, which are known to enhance learning. The sustainability module was reviewed by a panel of experts to establish content validity.

Finally, the five-part, learning-cycle-based sustainability module was incorporated into CEE capstone and cornerstone design courses. Comparing student-generated concept maps and/or student survey responses before and after participation in activities supported that both cohorts were able to improve their conceptual knowledge and sustainable design confidences. However, improvements were significantly greater for cornerstone students, as compared to capstone students. Even still, the cornerstone cohort indicated that they enjoyed participating in the module substantially more than seniors. Consequently, the sustainability module was deemed most appropriate for future implementation in CEE cornerstone design courses.

While results of this project are especially important for CEE at Georgia Tech, other programs and institutions may also benefit. For instance, the use of student surveys were established to be comparable to licensed curricular assessments, which may provide program leaders with a less expensive alternative for preliminary curricular assessments. In addition, presentation of several cmap scoring methods and the Sustainable Design Rubric provide others with tools for obtaining relatively objective measures of students' conceptual and applied knowledge of sustainability. Finally, the sustainability module, which was theoretically-grounded and empirically-verified, may aid other programs in integrating sustainability into their own engineering courses.

CHAPTER ONE

INTRODUCTION

As the global landscape continues to evolve, engineers will be required to adapt their skills and professional practices to meet the needs of present and future generations. Specifically, engineers are increasingly called upon to develop and implement innovative solutions that serve a growing population, while simultaneously exploiting fewer resources and minimizing environmental impacts. However, a committee commissioned by the National Academy of Sciences (NAS) posited that tackling complex global dilemmas will "challenge" the skills and creativity of traditionally-trained engineers [1, 2]. As a result, a transformation of engineering education is needed to educate engineers to operate under a sustainable development paradigm by considering sustainability issues throughout the design process [1]. While such an educational revolution is daunting, results from engineering education research can aid in designing empirically-supported reform efforts.

Sustainable Development and Engineering Education

Sustainable Development

Sustainable development has emerged as a promising strategy for combating alarming trends (population growth, resource consumption, poverty, and environmental degradation) that threaten society's long-term survival. The most widely accepted definition of sustainable development, published by the United Nations (UN) World Commission on Environment and Development in 1987, states that sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. The Johannesburg Declaration, released after the UN World Summit on Sustainable Development, later proposed the three pillars of sustainable development to be economic development, social development, and environmental protection [4]. While endorsing sustainability requires valuing all three dimensions, it has been suggested that the environmental dimension is often over-emphasized [5-9], while the less academically-developed social dimension is underemphasized [10]. Some authors have suggested that additional dimensions should be added to the three-pillars conceptual framework, including temporal [11] and institutional dimensions [12]. Nevertheless, the dimensions of sustainability are complex and interrelated, and promoting sustainable development requires that tradeoffs between all dimensions be simultaneously balanced.

Sustainable Engineering

Although technological innovation has contributed to unsustainable practices, sustainable engineering, through sustainable design, is important for developing and implementing sustainable development strategies. Sustainable engineering has emerged as a new field aimed at integrating and balancing economic, environmental, and social systems during development [13]. While there may certainly be a new breed of engineers that identify themselves as sustainable engineers, practitioners from all engineering disciplines can promote sustainability through sustainable design [1].

Sustainable design is often heralded as the new design paradigm. Engineering design itself is described as "a creative decision-making process that aims to find an optimal balance of trade-offs in the production of an artifact that best satisfies customer and other stakeholder preferences" [14]. Sustainable design only requires that sustainability principles be incorporated into this complex decision-making process to promote consideration of and balance between the three sustainability pillars. Describing this innovative approach to design, Skerlos et.al. [14] states that sustainable design "brings focus" to the design process, while McLennan [15] describes that sustainable design "expand[s] the definition of good design to include a wider set of issues." Thus, designing for sustainability is not an alternative to traditional engineering design; rather, it is a more holistic design paradigm. Many organizations, including the National Research Council (NRC) [16], the National Science Foundation (NSF) [17], and the National Institute of Standards and Technology [18], recognize the importance of the sustainable design paradigm to the advancement of global sustainability.

Sustainability and Engineering Education

For sustainable engineering to effectively contribute to global sustainability, engineering curricula must be updated to properly train engineers to understand and apply sustainability concepts during design. Current curricula in higher education emphasize disciplinary specialization and reductionist thinking [19-21]. As a result, many graduates are "unbalanced, over-specialized, and mono-disciplinary graduates" who use their narrow skill sets to solve problems by analyzing system components in isolation [21]. In contrast, the complex nature of global and local dilemmas necessitates that sustainable engineers exercise interdisciplinary and systems thinking to understand and balance the interrelated technical, economical, environmental, and social dimensions of a problem [22]. For instance, alleviation of global problems of resource scarcity and environmental degradation in the context of a growing population requires a broad knowledge base and the ability to analyze problems holistically [22]. Thus, significant changes in engineering education, which are supported by professional organizations including the American Society of Civil Engineers (ASCE), are needed to equip students to tackle complex problems [23].

Engineering Education Research

Discipline-based education research (DBER) can provide important insights for improving technical higher education, including the teaching and learning of sustainability concepts and skills. The purpose of DBER, which has emerged in physics, chemistry, biology, geosciences, astronomy, and engineering, is to investigate how students learn different disciplines and how instruction can support learning. While key DBER findings have been reported, including the effectiveness of student-centered learning strategies, much effort is still needed to integrate findings into mainstream science and engineering education for the purpose of enhancing student learning [24].

Engineering education, specifically, is a developing field [25, 26] aimed at conducting rigorous DBER within engineering. The "grand challenge" of engineering education revolves around the question: "How will we teach and how will our students learn all that is needed to tackle the challenges of today and tomorrow?" [27]. To aid in tackling this challenge, five key research areas have been identified as the foundations of engineering education research: engineering epistemologies, engineering learning mechanisms, engineering learning systems, engineering diversity and inclusiveness, and engineering assessment (Table 1.1) [2]. Research into these areas will help educators gain a more holistic and empirically-supported perspective on student learning in engineering.

Table 1.1. Five research areas for Engineering Education (Adapted from [2]).

Research Area	Description	Sample Questions
Engineering Epistemologies	• Research on what constitutes engineering thinking and knowledge within social contexts now and into the future.	• Where *do* and where *should* engineers learn core elements, and who is involved in these decisions?
Engineering Learning Mechanisms	• Research on engineering learners' developing knowledge and competencies in context.	• What knowledge, skills, and attitudes do learners bring to their engineering education that influences what (and how) they learn?
Engineering Learning Systems	• Research on the instructional culture, institutional performance, and epistemology of engineering educators.	• What instructional theories can guide the engineering education communities in making decisions about the education system that are most effective for engineering learners?
Engineering Diversity and Inclusiveness	• Research on how diverse human talents contribute solutions to the social and global challenges and relevance of our profession.	• How can the design of learning environments and curricula capitalize on diverse learning styles?
Engineering Assessment	• Research on, and the development of, assessment methods, instruments, and metrics to inform engineering education practice and learning.	• What do valid and reliable assessments reveal about engineering as a profession, student engagement and learning, and teaching methods and systems?

Project Outline

This project aims to use engineering education research as a vehicle for improving sustainability education within civil and environmental engineering (CEE). Using the School of CEE at the Georgia Institute of Technology (Georgia Tech) as a case study, the broad research goals are to assess and improve sustainability education through three different phases of inquiry: (1) benchmarking the current status of CEE sustainability education, (2) using results from curricular and student knowledge assessments to design a sustainability module to guide students in learning about and applying sustainability concepts, and (3) assessing the impacts of integrating the sustainability module into CEE courses on student learning. Research questions within each phase of inquiry (Table 1.2) align with one or more of the five key engineering education research areas (Table 1.1). While the study certainly provides specific results for Georgia Tech, broad implications for CEE and other engineering programs in general will be presented.

Table 1.2. Research outline, including engineering education research areas addressed.

Research Goal	Research Question	Research Tool(s)	Relevant Chapter	Engr Ed Research Area
Inquiry #1: Examine the current status of CEE sustainability education.	Question 1.1: What do students' perspectives reveal about sustainability education?	Student Sustainability Survey	Chapter 4: Analyzing Student Perceptions of CEE Sustainability Education	Engineering Learning Mechanisms
	Question 1.2: To what extent is sustainability currently integrated into the CEE curriculum?	STAUNCH® system; Student Curriculum Survey; Student Sustainability Survey	Chapter 5: Examining the Sustainability Content of the CEE Curriculum	Engineering Epistemologies; Engineering Assessment
	Question 1.3: How advanced is students' conceptual understanding of sustainability?	Concept-map-based knowledge assessments; Student Sustainability Survey	Chapter 6: Analyzing Undergraduates' Conceptual Sustainability Knowledge	Engineering Learning Mechanisms; Engineering Assessment
	Question 1.4: How proficient are CEE seniors in their abilities to engage in sustainable design?	Sustainable Design Rubric; Student Sustainability Survey	Chapter 7: Investigating the Abilities of Undergraduates to Engage in Sustainable Design	
Inquiry #2: Design an empirically-informed and pedagogically-innovative sustainability module.	Question 2.1: How should an educational intervention be designed to be sensitive to the results of curricular and student knowledge assessments, as well as best practices in teaching and learning?	N/A	Chapter 8: Development of a Module for Teaching Sustainability 'Around the Cycle'	Engineering Learning Systems
Inquiry #3: Investigate the impacts of integrating the sustainability module into select CEE courses.	Question 3.1: To what extent can integration of a learning-cycle-based sustainability module into a CEE capstone design course improve student knowledge?	Concept-map-based knowledge assessments; Sustainable Design Rubric; Student Sustainability Survey; Module Evaluation Survey	Chapter 9: Impacts of Implementing a Learning-Cycle-Based Sustainability Module into a CEE capstone design course	Engineering Learning Systems
	Question 3.2: To what extent can integration of a learning-cycle-based sustainability module into a CEE cornerstone design course improve student knowledge?	Concept-map-based knowledge assessments; Student Sustainability Survey; Module Evaluation Survey	Chapter 10: Impacts of implementing a learning-cycle-based sustainability module into a CEE cornerstone design course	
	Question 3.3: Is the sustainability module best suited for integration into CEE capstone or cornerstone design courses?	Concept-map-based knowledge assessments; Student Sustainability Survey; Module Evaluation Survey		

CHAPTER TWO

LITERATURE REVIEW

Chapter Overview

To aid in development, implementation, and analysis of a project to assess and improve sustainability education within CEE, a comprehensive literature review was conducted. First, current ideas related to sustainable development and sustainability were investigated to explore the content that may be relevant for engineers and engineering students. Second, the emerging field of sustainability engineering and science itself was defined and further researched. Finally, innovations specifically related to sustainability education within engineering were examined.

Sustainable Development and Sustainability

Emergence of Sustainable Development and Sustainability as Global Issues

World Population

The Earth's population is rapidly growing. According to the World Bank, the population reached 6.97 billion people in 2011 [28] and is expected to exceed 9 billion by 2050 [29]. The UN Fund for Population Activities cites that rising population is attributed to lower infant mortality rates, increased life expectancies, and higher fertility [30]. Furthermore, between 2009 and 2050, the population in developing countries is expected to increase from 5.6 to 7.9 billion people, while the population in developed countries will likely rise from 1.23 to 1.28 billion people [30]. Indeed, population growth will be a key issue in the future, especially in developing regions.

Population and Resource Consumption

Increasing global population often requires increased resource consumption to meet basic human needs. Developing countries currently use fewer resources per capita than developed countries. For example, the per capita energy use in the United States (US) is 87,216 kWh, as compared to 18,608 kWh in China and 6280 kWh in India [31]. Similarly, per capita water consumption in the United States is 575 L/day, as compared to 86 L/day in China, and 135 L/day in India [32]. If resource availability permits, developing countries may become more populated and industrialized, which could increase their future consumption [33]. Thus, the developed world will continue to rapidly consume natural resources, while total resource requirements in the developing world will increase due to increases in population and affluence.

Resource Consumption and Environmental Degradation

One consequence of rapid resource consumption historically has been environmental degradation. For example, combustion of fossil fuels for energy has produced increasing carbon dioxide emissions, which may contribute to global climate change. Deforestation and changing land use for urbanization and food cultivation has compounded the problem by decreasing the capacity of natural carbon sinks. In addition, energy generation and industrial activities have diminished the quality of air and water, although environmental regulations in many countries have sought to protect these resources. Nevertheless, unbounded resource consumption to support the global population may have several adverse impacts on the environment [3].

Tragedy of the Commons and Sustainable Development

The current patterns of population growth, resource consumption, and environmental degradation cannot be sustained indefinitely. While sufficient resources may currently exist to maintain the status quo, the lifetimes of natural resources are uncertain, especially given the future industrialization of developing countries [34]. According to Hardin in *The Tragedy of the Commons*, there exists a natural phenomenon whereby individuals deplete limited, shared resources, despite the fact that they are dependent on the resources for survival [35]. Current events seem to support Hardin's proposition, as individuals continually exploit shared natural resources. As a result, in the absence of changes in global behavior, it is likely that resource scarcity and environmental degradation will significantly affect future generations.

Global adoption of a sustainable development paradigm is an emerging strategy for combating the Tragedy of the Commons. In short, sustainable development endorses economic and social advancements which protect the natural environment [36]. The UN has been active in endorsing and defining sustainable development through organization of international conferences and publication of landmark documents (Figure 2.1).

Fundamental Definitions

Numerous definitions for sustainable development have been proposed (Figure 2.1). The most widely accepted definition was published in *Our Common Future*, a 1987 document prepared by the UN World Commission on Environment in Development (also known as the Brundtland Report). The Report stated that sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. Several organizations have proposed similar definitions that cite the need for intergenerational equity, such as the NRC who states that sustainable development is "the reconciliation of society's developmental goals with the planet's environmental limits over the long term" [16]. Many critics argue that such general definitions of sustainable development are too broad and non-descriptive [7, 37].

Sustainability can be viewed as the goal of sustainable development (Table 2.1). When present requirements are fulfilled while ensuring intergenerational equity, sustainability is achieved [36]. Similarly, a sustainable society is "one that can persist over generations, one that is far-seeing enough, flexible enough, and wise enough, not to undermine either its physical or its social systems of support" [33]. Sustainability and sustainable development are often used interchangeably to describe the quest for becoming a sustainable society.

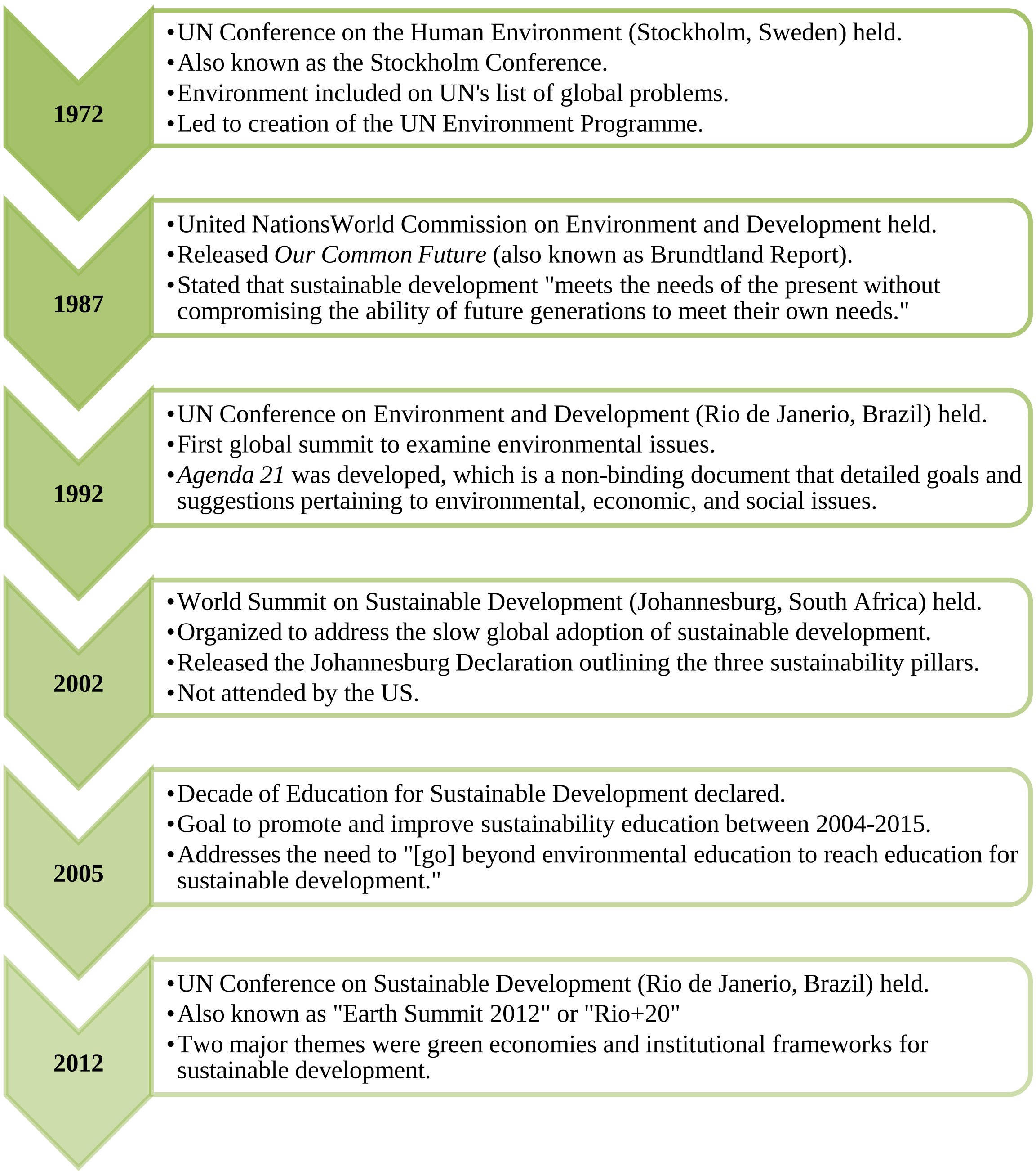

Figure 2.1. United Nations' sustainability-related initiatives.

Table 2.1. Summary of sustainable development and sustainability definitions.

Term	Definition	Organization/Author	Source
Sustainable Development	• Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.	• Brundtland Report	[3]
	• Improving the quality of human life while living within the carrying capacity of supporting ecosystems.	• World Conservation Union	[38]
	• Development that delivers basic environmental, social, and economic services to all residences of a community without threatening the viability of natural, built, and social systems upon which the delivery of those systems depends.	• International Council for Local Environmental Initiatives	[39]
	• Approach to environmental and development issues that seeks to reconcile human needs with the capacity of the planet to cope with the consequences of human activities.	• Royal Academy of Engineering	[34]
	• The process of applying natural, human, and economic resources to enhance the safety, welfare, and quality of life for all of society while maintaining the availability of the remaining natural resources.	• American Society of Civil Engineers	[40]
Sustainability	• Goals or endpoints of sustainable development.	• Diesendorf	[36]
	• Design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment.	• Mihelcic et al.	[13]
	• The indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructure and institutions which distribute and protect the components of these systems.	• Liverman et al.	[41]

Conceptual Frameworks

<u>The Three Pillars of Sustainable Development</u>

Emergence and Acceptance

To clarify the broad definition of sustainability, a conceptual framework describing sustainable development as being composed of three major dimensions has been proposed. Early authors [42, 43] and documents put forth by the UN (*Our Common Future* and *Agenda 21*) discuss the economic, environmental, and social aspects of sustainable development [3, 44]. Elements of the three dimensions of sustainability are also evident in the NRC's *Our Common Journey*, with the need to consider both resources that should be developed (people, economy, and society) and assets that should be sustained (nature, life support, and society) being discussed (Figure 2.2) [16]. However, it was the 2002 Johannesburg Declaration that first proposed the "three pillars" of sustainable development, which include economic development, social development, and environmental protection [4]. Many organizations and academic authors have since adopted the three-pillars framework for sustainable development [36, 45, 46].

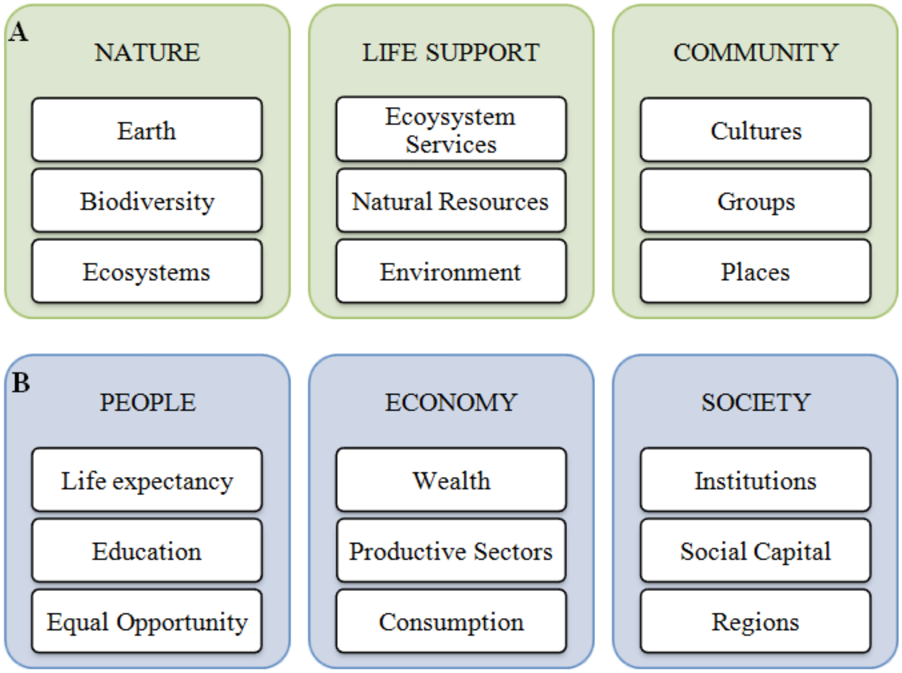

Figure 2.2. Description of items (A) to be sustained and (B) to be developed when engaging in sustainable development [16].

Description and Analysis of the Three Pillars

The three sustainability pillars have been widely debated in order to provide general guidelines for promoting sustainable development. Economic sustainability requires that a development maintain or improve economic welfare, while environmental sustainability dictates conservation of natural resources. A project is classified as socially sustainable if it improves social equity and provision of services (Table 2.2) [43, 46]. While the pillars clarify the notion of sustainability, they also complicate the operational pursuit of sustainable development. With most projects yielding impacts on each the environment, economy, and society, it is almost inevitable that protecting the interests of one dimension may come at the expense of another. For instance, projects that are environmentally-sound may be more expensive than alternatives, which may increase the financial burden on economically-disadvantaged populations. As a result, the normative nature of the three pillars makes the analytical evaluation of sustainable development difficult. Nevertheless, some experts argue that efforts to consider and balance the impacts to each pillar are necessary, even if conflicts must be ultimately resolved through compromise [46].

Table 2.2. Criteria for a development to comply with the three sustainability pillars [46].

Sustainability Pillar	Criteria for Fulfillment
Economic	An economically sustainable system must be able to: • Produce goods and services on a continuing basis. • Maintain levels of government, and external debt. • Avoid extreme sectoral imbalances which damage agricultural or industrial production.
Environmental	An environmentally sustainable system must: • Maintain a stable resource base. • Avoid over-exploitation of renewable resource systems or natural sinks. • Avoid depleting non-renewable resources only to the extent that investment is made in adequate solutions.
Social	A socially sustainable system must achieve: • Distributional equity. • Adequate provision of social services, including health, education, gender, equity, and political accountability.

Models Describing the Three Pillars

Two common models for describing the connections between the three pillars are the Sustainability Venn Diagram and the Nested Dependencies Model (Figure 2.3). The Venn diagram representation, also called the Triple Bottom Line Model [47], depicts that sustainable development requires a balance between the separate sectors of environment, society, and economy [37, 39, 47, 48]. Balance between economic and environmental goals is known as eco-efficiency, while fair trade describes economic development in the context of social consequences [49]. Environmental justice occurs when an optimal balance is reached between social equity and environmental protection [49]. For sustainability to be achieved, the goals of all three sustainability sectors must be considered. The Sustainability Venn Diagram is criticized because it deemphasizes sector interdependencies by assuming that each dimension is autonomous [37, 43, 47]. Furthermore, the Venn diagram depiction unfoundedly suggests that achievement of eco-efficiency, fair trade, and environmental justice will lead to sustainability [49]. The Nested Dependencies Model overcomes these shortcoming by depicting that the economy exists within society, which resides within the environment [47]. Thus, the Nested Dependencies Model may provide a more holistic view of sustainable development than the Sustainability Venn Diagram.

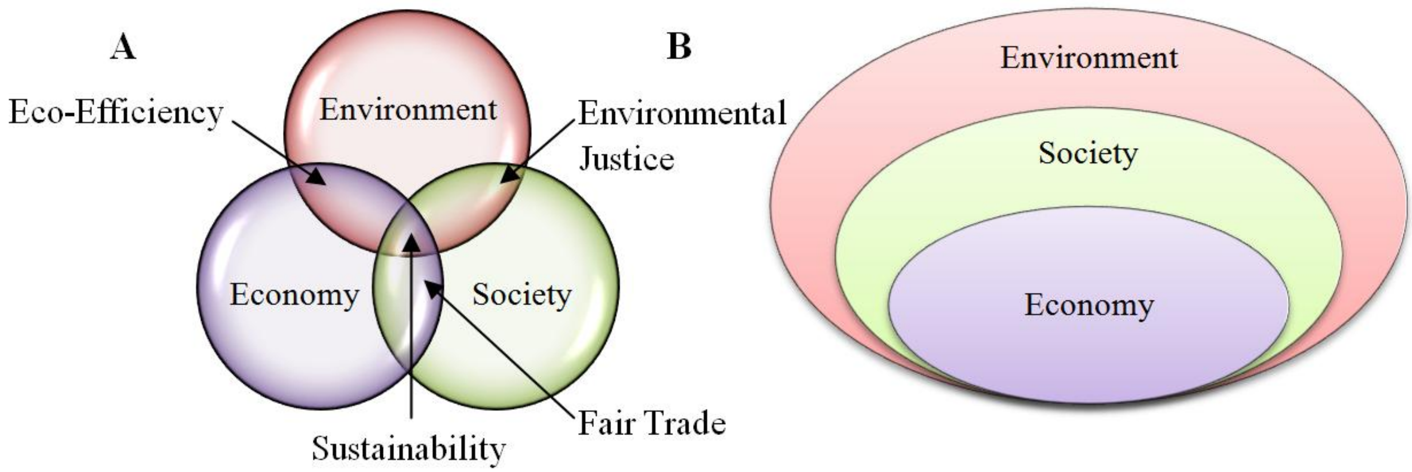

Figure 2.3. Models describing the interrelationship between the three pillars of sustainability, including (A) the Sustainability Venn Diagram (Triple Bottom Line Model) and (B) the Nested Dependencies Model.

Five-Capitals Framework

Emergence and Acceptance

The economically-rooted five-capitals model is an alternative framework used to describe sustainability. Early authors [50] and economists [51] originally proposed that natural, human, social, and manufactured capital are available for use in development. Financial capital was later added to the model [52, 53]. The five-capitals model explains that sustainable development requires equal investment in each type of capital. Conversely, development is not sustainable when investments are made unequally between capitals [47, 52, 53].

Description and Analysis of the Five Capitals

The five types of capital are used to categorize the many assets that can be used for developments. Human capital describes those intangible items that allow for human productivity, while social capital includes social institutions which support human capital. Natural capital includes all environmentally-derived resources, which may be used to produce manufactured capital. Financial capital, while not having intrinsic value, is used to allow for ownership and trading of other capitals [47, 52, 53] (Table 2.3).

The five types of capital represent interdependent assets. First, social capital is derived from human capital, while manufactured capital is produced from natural capital. Second, financial capital relies on both natural and human capital for value. Finally, it may be argued that humans, and by extension human capital, are also derived from natural capital since they are composed of elemental materials. Thus, all types of interrelated capital may be dependent on natural capital for persistence [47].

Table 2.3. Description of five types of capitals that are available for sustainable development (Adapted from [47, 52]).

Capital	Description
Natural	Includes environmentally-derived assets, including natural resources (e.g. fossil fuels and vegetation) and services (e.g. climate regulation).
Human	Includes intangible items that contribute to one's well-being and productive output (e.g. health, knowledge, skills, motivation).
Social	Includes the institutions and organizational frameworks (e.g. families, governments, schools) that serve to maintain human capital.
Manufactured	Includes infrastructure or fixed assets which are not final goods, but rather used in the production process (e.g. tools, machines, roads, buildings).
Financial	Although it has no intrinsic value, it allows for a measure of the productive potential of other capitals and allows capitals to be owned and traded.

<u>Integrating Sustainability Frameworks</u>

The Three Pillars and Five Capitals Frameworks are easily reconciled (Figure 2.4). Natural capital can be considered to compose the environmental dimension, while manufactured and financial capitals are used in the economic sector. In addition, social and human capitals comprise the social dimension. Although the Five-Capitals Framework can be integrated into either the Sustainability Venn Diagram (Figure 2.4A) or the Nested Dependencies Model (Figure 2.4B), the dependence of all capital on natural capital may further support appropriateness of the Nested Dependencies Model.

An integrated sustainability framework can be used to more clearly explain the classic Brundtland definition of sustainable development (Figure 2.1). Important elements of sustainable development include intergenerational equity [3], balance between the three dimensions of development [4], and equal investment in the five types of capital. Thus, sustainable development may be described as development that ensures intergenerational equity by equally investing in natural, social, human, manufactured, and financial capitals to provide balance between economic development, social development, and environmental protection.

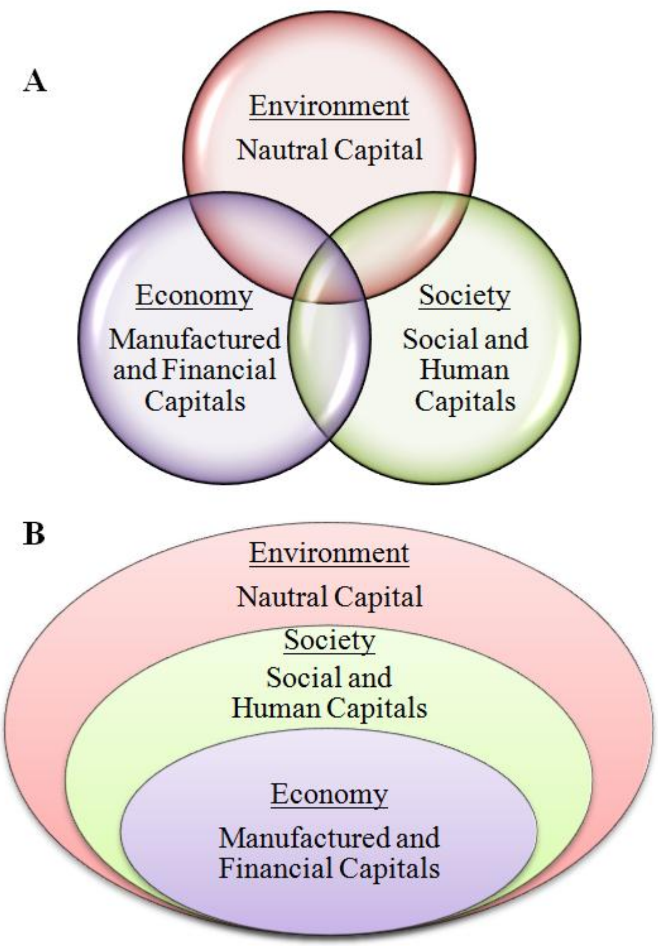

Figure 2.4. Sustainability model incorporating Three Pillars and Five Capitals Frameworks.

Hierarchy of Unsustainable Actions

While much discussion often centers around sustainable development, understanding sustainability can be further enhanced by examining unsustainable practices. The Sustainability Hierarchy, based on Abraham Maslow's Hierarchy of Needs, categorizes unsustainable actions into four categories (Figure 2.5). Level 1 actions include practices that threaten fundamental environmental sustainability, while upper level actions violate higher-order sustainability needs, such as human health, welfare, and rights. Categorization of unsustainable practices into appropriate levels is somewhat subjective, especially when values and beliefs must be considered (Level 4). Nevertheless, the identification and classification of unsustainable practices serves to further elucidate the often abstract concept of sustainable development [49].

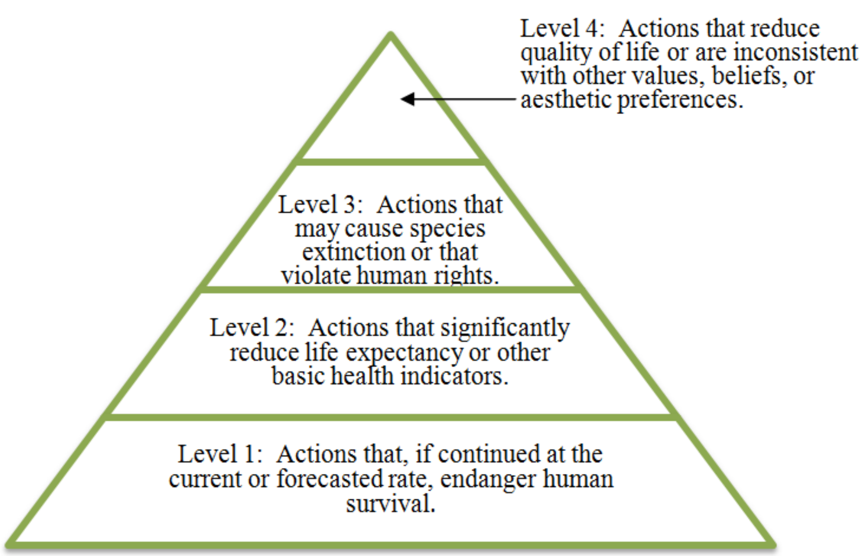

Figure 2.5. Hierarchy of Unsustainable Actions, which depicts the most unsustainable practices and most basic sustainability needs at the bottom [49].

Sustainability Science and Engineering

Emergence of a New Discipline

Although technological innovation has contributed to current unsustainable practices, science and engineering can be especially instrumental for developing and implementing sustainable development strategies. Sustainability science and engineering (SSE) has emerged as a new field aimed at integrating and balancing economic, environmental, and social systems during global development. Furthermore, SSE is considered to be a "metadiscipline" because knowledge required to develop and advance the field transcends understanding of any single natural science, social science, or engineering specialty [13]. SSE has been recognized by many organizations, including the NRC [16], the National Science Foundation (NSF) [17], and the National Institute of Standards and Technology (NIST) [18].

Foundations in Green Science and Engineering

SSE has foundations in green Science and Engineering (GSE), which is a field that seeks to use science and engineering to protect and improve the natural environment. According to a consensus reached at the Sandestin Green Engineering Conference, GSE "incorporates the development and implementation of technologically and economically viable products, processes, and systems to promote human welfare while protecting human health and elevating the protection of the biosphere as a criterion in engineering solutions" [54]. The Twelve Principles of Green Chemistry and the Twelve Principles of Green Engineering (Table 2.4) were developed to aid in development of such environmentally-sound solutions [55-57].

SSE requires consideration of the three dimensions of sustainability during development, while GSE focuses primarily on economic development and environmental protection. First, as is common during project design, both disciplines acknowledge the importance of economic feasibility. Second, both GSE and SSE advocate for environmental protection using strategies such as reducing waste (pollution prevention) and holistically examining products and processes (industrial ecology). However, the environmental dimension of SSE also acknowledges that such strategies are insufficient if biological limits, such as the Earth's carrying capacity, are exceeded [13]. Third, unlike GSE, SSE integrates social implications into project decision making [58]. As a result, SSE provides a more holistic approach to development than GSE, and can be considered to exist at the intersection of sustainability and GSE (Figure 2.6).

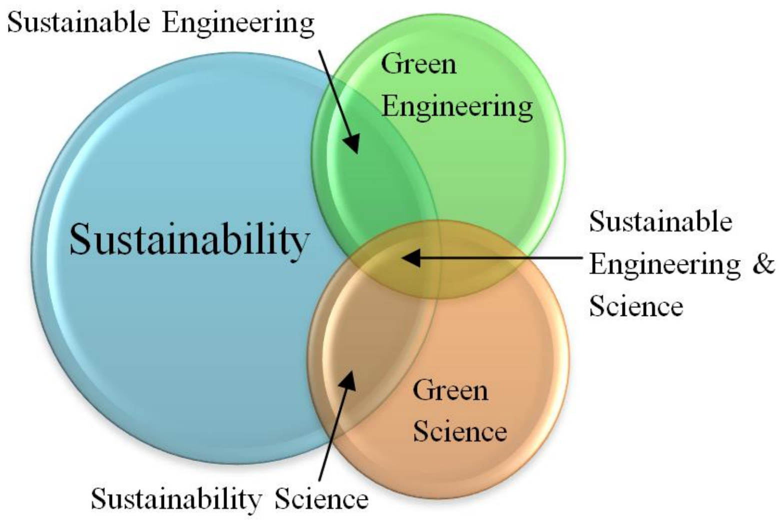

Figure 2.6. Relationship of green engineering and science to sustainability (Modified from [58]).

Table 2.4. Twelve Principles of Green Engineering [56].

Brief Description	Principle
Inherent Rather than Circumstantial	Strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
Prevention Instead of Treatment	It is better to prevent waste than to treat or clean up waste after it is formed.
Design for Separation	Separation and purification operations should be designed to minimize energy consumption and materials use.
Maximize Efficiency	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
Output-Pulled Versus Input-Pushed	Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
Conserve Complexity	Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
Durability Rather than Immortality	Targeted durability, not immortality, should be a design goal.
Meet Need, Minimize Excess	Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
Minimize Material Diversity	Material diversity in multi-component products should be minimized to promote disassembly, value retention.
Integrate Material and Energy Flows	Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
Design for Commercial Afterlife	Products, processes, and systems should be designed for performance in a commercial "afterlife."
Renewable Rather than Depleting	Material and energy inputs should be renewable rather than depleting.

Sustainability Science

Sustainability science is a rapidly evolving field aimed at applying science and technology to sustainable development. The Johannesburg Declaration called on scientists to devise sustainable solutions to global dilemmas with the same success that has already been achieved in using scientific principles to identify un-sustainable practices [4, 59]. Thus, sustainability science has emerged with the goal of studying dynamic interactions between nature and society [59-61]. Similar to the areas of agricultural science and health science, sustainability science is "defined by the problems it addresses rather than the disciplines it employs" [61]. Sustainability science not only supports promising research, but it also provides science-based sustainability principles and metrics to aid experts in solving problems in a sustainable manner.

Sustainability Science Research

Sustainability science is an area with ambitious research goals aimed at promoting sustainability. According to Stoke's classification, scientific research can be either basic, applied, or use-inspired basic, depending on the inspiration for the scientific work. Sustainability science qualifies as use-inspired basic research because it is motivated by both the quest for fundamental understanding and the consideration of use [61]. As a result, a series of seven core sustainability science research questions have been proposed that seek to gain fundamental understanding as a means for devising sustainable solutions (Table 2.5) [60, 62]. Important research objectives include development of scientifically-based sustainability principles (question no. 1) and identification of sustainability metrics for characterizing progress towards sustainability (question no. 6).

Table 2.5. Core sustainability science research questions [60, 62].

No.	Core Research Question
1	How can the dynamic interactions between nature and society—including lags and inertia—be better incorporated into emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
2	How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?
3	What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
4	Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
5	What systems of incentive structures—including markets, rules, norms, and scientific information—can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6	How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
7	How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?

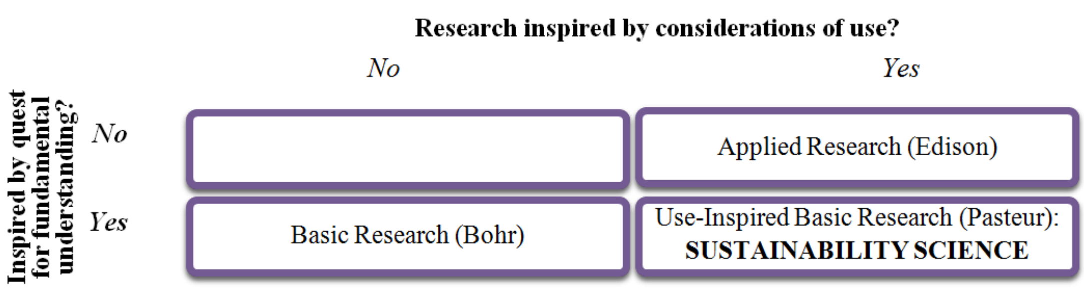

Figure 2.7. Classification of sustainability science using Stoke’s quadrants [61, 63].

Science-Based Sustainability Principles

Natural Step Framework

The Natural Step framework was developed based on scientific principles to guide sustainability-directed activities. Pioneered by Dr. Karl-Henrik Robèrt, the Natural Step Framework provides a set of conditions for sustainable systems founded on the fundamental laws of thermodynamics (Table 2.6). The first three system conditions provide requirements for a sustainable relationship between humans and the environment, while the fourth condition may relate to social and/or economic sustainability. Originally endorsed by over 50 Swedish scientists, the Natural Step Framework has now been adopted by numerous organizations and academics [64].

Table 2.6. Natural Framework system conditions and sustainability principles [64].

No.	System Condition (In a sustainable society…)	Sustainability Principle (To become a sustainable society, we must…)
1.	Nature is not subject to systematically increasing concentrations of substances extracted from Earth's crust.	Eliminate our contribution to the progressive buildup of substances extracted from the Earth's crust (e.g. heavy metals and fossil fuels).
2.	Nature not subject to increasing concentrations of substances produced by society.	Eliminate our contribution to the progressive buildup of chemicals and compounds produced by society (e.g. dioxins)
3.	Nature is not subject to systematically increasing degradation by physical means.	Eliminate our contribution to the progressive physical degradation and destruction of nature and natural processes (e.g. harvesting forests and paving over habitats).
4.	People are not subject to conditions that systematically undermine their capacity to meet their needs.	Eliminate our contribution to conditions that undermine people's capacity to meet their basic human needs (e.g. unsafe work conditions).

Principles of Biomimicry

Biological principles can also be used to formulate sustainability requirements. For billions of years, biota have been evolving solutions to common problems, such as climate control and non-hazardous manufacturing [65]. Thus, rather than developing novel solutions to global problems, sustainable strategy "templates" can be borrowed from nature [66]. Biologically-inspired solutions often adhere to the Principles of Biomimicry, which summarize nature's key sustainable characteristics (Table 2.7) [67]. Alternatively, the Biomimicry Guild has proposed that biologically-based sustainability should adhere to the Principles of Life (Table 2.7) [68]. By using biological principles as a basis for sustainability, it is probable that the developed technology will be easily integrated into the natural environment [66]. Thus, the Principles of Biomimicry and the Principles of Life summarize biological observations that can be used as a basis for understanding sustainability.

Table 2.7. Summary of the Principles of Biomimicry and the Principles of Life, which describe the basis for natural sustainability [67, 68].

Biomimicry Principle	Principles of Life
Nature runs on sunlight.	Optimizes rather than maximizes
Nature uses only the energy it needs.	Leverages interdependence
Nature fits form to function.	Benign manufacturing
Nature rewards cooperation.	Resilient
Nature banks on diversity.	Integrates cyclic processes
Nature demands local expertise.	Locally attuned and responsive
Nature curbs excesses from within.	
Nature taps the power of limits.	

Metrics for Quantifying Sustainability

Application of scientifically-based sustainability principles is often facilitated by the use of sustainability metrics. Both sustainability indicators and sustainability indexes are available for formally assessing the sustainability of developments.

Sustainability Indicators

Sustainability indicators are commonly used to characterize sustainability. Indicators describe a phenomenon that cannot directly be measured or classified, while a variable represents a parameter that can be directly observed. Since sustainability is not easily measured, surrogate variables, or sustainability indicators, are often used to make inferences regarding sustainability or unsustainability [69, 70].

Three scales are often used to describe sustainability indicators. First, normative scales include only two classifications (such as “yes” or “no”), while ordinal scales consist of a variety of qualitative classifications. Quantitative cardinal scales are preferred for sustainability indicators because the distance from a sustainability goal can be calculated. Useful cardinal scale indicators can be applied to any situation, are indicative of the phenomenon they represent, and are sensitive to changes in the indicated event. Much research has centered around the specification and measurement of quantitative sustainability indicators, including those related to economic, environmental and social sustainability [70, 71] (Table 2.8).

Table 2.8. Economic, environmental, and social sustainability indicators [71].

Economic Indicators	Environmental Indicators	Societal Indicators
Direct:	Material Consumption:	Quality of Life:
Raw material costs	Product/packaging mass	Breadth of product/service availability
Labor costs	Useful product lifetime	Knowledge enhancement
Capital costs	Hazardous materials used	Employee satisfaction
Operating costs	Eco-efficiency	
Potentially Hidden:	Energy consumption:	Peace of Mind:
Recycling revenue	Life cycle energy	Perceived risk
Product disposition cost	Power use in operation	Community trust
Contingent:	Local impacts:	Illness and Disease Reduction:
Employee injury cost	Product recyclability	Illnesses avoided
Customer warranty cost	Runoff to surface water	Mortality reduction
Relationship:	Regional impacts:	Safety Improvement:
Customer retention	Smog creation	Lost-time injuries
Business interruption due to stakeholder interventions	Acid rain precursors	Reportable releases
	Biodiversity reduction	Number of incidents
Externalities:	Global Impacts:	Health and Wellness:
Ecosystem productivity loss	Global warming emissions	Nutritional value provided
Resource depletion	Ozone depletion	Subsistence costs

Sustainability Indexes

Sustainability indexes can also be used to gauge progress toward sustainability. Indexes are parameters that combine several indicators to provide summarized information about a problem or event. For instance, the Human Development Index, developed by the UN Development Programme, combines measures of life expectancy, literacy, and education to rate the level of human well-being in a country. The Environmental Performance Index combines indicators related to ecosystem vitality and environmental health to rank the environmental sustainability of a country. Even still, the Genuine Progress Index, an alternative to the commonly-used gross domestic product, uses a set of indicators to quantify economic growth that has translated into social development. Thus, numerous sustainability indexes are available for characterizing the quality of development activities.

Sustainable Engineering and Design

In addition to sustainability science, sustainable engineering can also contribute to a sustainable future. Specifically, through engagement in sustainable design with appropriate methods, adherence to sustainable design principles, and use of sustainable design tools, engineers can be especially effective at developing sustainable solutions to global problems.

<u>Sustainable Design</u>

Sustainable engineering can contribute to sustainable development through creation and implementation of sustainable designs. Engineering design is defined as "a creative decision-making process that aims to find an optimal balance of trade-offs in the production of an artifact that best satisfies customer and other stakeholder preferences" [14]. Integration of sustainability principles into the design process results in sustainable design, which is the development of products, processes, and services that promote intergenerational equity through promotion of the three sustainability pillars [14]. More abstractly, sustainable design is "the conception and realization of environmentally sensitive and responsible expression as a part of the evolving matrix of nature" [72]. Designing for sustainability is not an alternative to traditional engineering design; rather, it is a new design paradigm. Describing the sustainable design paradigm, Skerlos et.al. [14] state that sustainable design "brings focus" to the design process, while McLennan describes that sustainable design "expand[s] the definition of good design to include a wider set of issues" [15]. Overall, engineers can promote sustainable development through engagement in sustainable design.

Sustainable Design Methods

Since sustainable design is a complement to existing design protocols, the traditional design process can be used to design for sustainability. The traditional methodology relies on principles such as the minimization of costs, space requirements, weight, and losses, as well as optimization of handling [73]. However, guidelines for sustainability (Figure 2.10) can be used to supplement the rational design process and traditional principles. Backcasting and biologically-inspired design methods have also been proposed as innovative design strategies to supplement the rational design procedure.

Rational Design Method

The rational engineering design process differs between engineering disciplines, although most methodologies are cyclical. For instance, the National Aeronautics and Space Administration (NASA) propose an eight-step procedure for engaging in engineering design that includes problem identification, research, development of design alternatives, design selection, model construction, design testing, design communication, and possible re-design (Figure 2.8A) [74]. Similarly, Mulder [70] describes a five-step method, which includes analysis, synthesis, simulation, evaluation, and decision-making

(Figure 2.8B). Consequently, traditional engineering design processes suggest progression from problem identification to design completion.

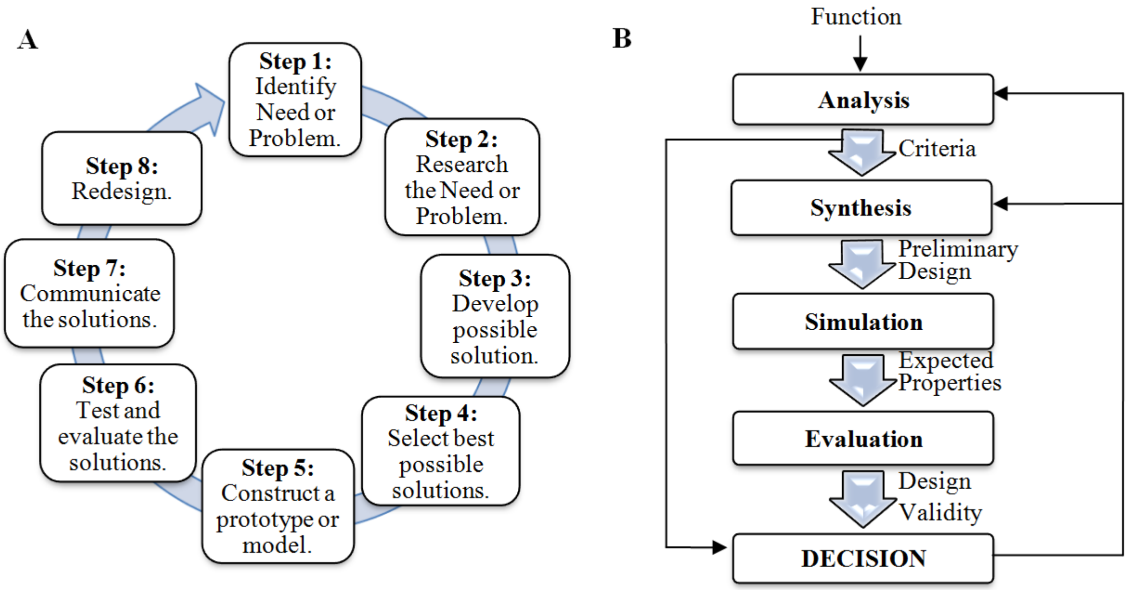

Figure 2.8. Engineering design processes proposed by (A) NASA and (B) Mulder [70].

Backcasting Design Method

Backcasting is a design strategy based on energy planning tools developed in the 1970's. In backcasting, the designer defines a future vision and then devises designs to fulfill the goal. A future vision is a normative description on how the future should be. In the context of sustainable design, the future vision from which to backcast is a sustainable society, which can be described using various sustainability principles (Table 2.10) [75].

Specific backcasting methods are the provided by Quist [76] and the Natural Step Framework [64]. Quist proposes a process for participatory backcasting, which involves the interested and affected stakeholders in development of the future vision. The five-step method for participatory backcasting includes strategic problem orientation, sustainable future vision construction, backwards-looking analyses, defining follow-up, and defining a follow-up agenda (Table 2.9). The Natural Step Framework procedure for backcasting is similar to that of Quist, except that the four system conditions for sustainability (Table 2.6) are suggested to define the future vision rather than stakeholder consensus (Table 2.9). Despite differences in methods, backcasting can be used to develop alternatives to aid in progression toward a sustainable future.

Table 2.9. Participatory and Natural Framework methods for backcasting [64, 76].

Participatory Backcasting	Natural Framework Backcasting
1. Strategic problem orientation. 2. Construction of sustainable future visions or scenarios. 3. Backwards-looking analyses. 4. Elaboration and definition of follow-up and action agenda. 5. Embedding of results and generation of follow-up.	1. Define a framework and criteria for sustainability. 2. Describe the current situation in relation to that framework. 3. Envision a future sustainable situation. 4. Find strategies for sustainability.

Biologically-Inspired Design Method

Biologically-inspired design is the application of biological principles in engineering design. A five-step design methodology, or "design spiral," can be used to guide engineers in adapting biological experience to technological innovation (Figure 2.9). First, the problem is *distilled* by formulating design functions and criteria. Next, the design specifications are *translated* into the biological realm by converting biological principles (Table 2.7) into design parameters. Third, research is completed to *discover* biological models that may provide important design insights. Once appropriate biological models have been identified, they are *emulated* to develop a design. Finally, the biologically-based design is *evaluated* against the Biomimicry Principles or the Principles of Life (Table 2.7). Similar to the rational design process, the "design spiral" may be repeated several times until an adequate solution is devised [65, 66].

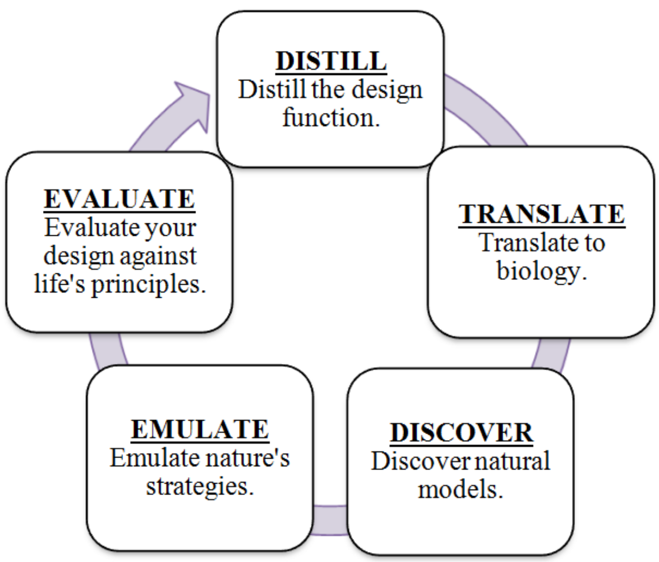

Figure 2.9. Process of biologically-inspired "design spiral" [65, 66].

Sustainable Design Principles

While sustainable design is increasingly popular, its global and intergenerational contexts can make it difficult to implement. Several organizations and authors have developed principles to operationalize sustainable design and guide engineers in creating sustainability-conscious designs. Many guidelines have been developed specifically for designers, including the Nine Principles of Sustainable Engineering and the Hannover Principles. In addition, engineers can gain important insights from science-based sustainability principles, GSE principles, and other sustainability principles (Figure 2.10). Despite the complex requirements for sustainable design, several resources are available to aid the design engineer.

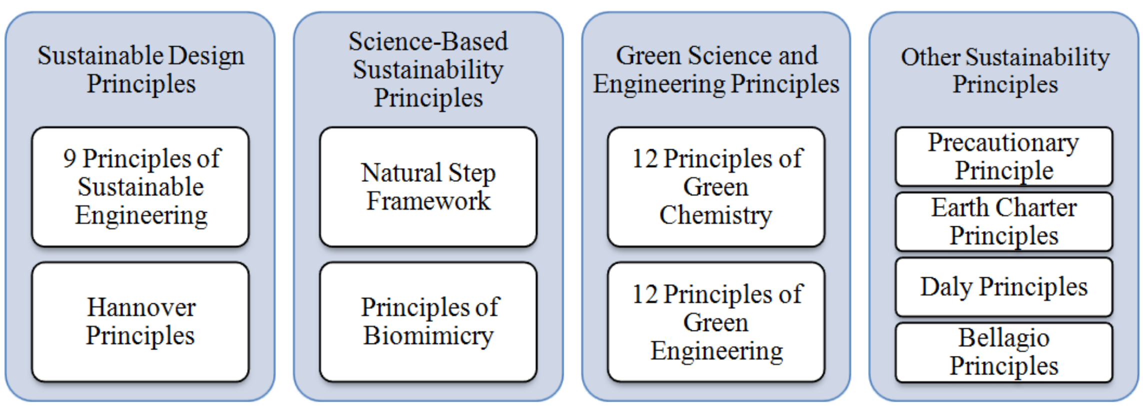

Figure 2.10. Sustainability-related principles that may be applied in the design process.

Nine Principles of Sustainability Engineering

Experts in SSE gathered at a 2002 Green Engineering Conference held in Sandestin, FL to devise a set of sustainable engineering design principles. The Nine Principles of Sustainable Engineering (Table 2.10) were proposed to "provide a paradigm in which engineers can design products and services to meet societal needs with minimal impact on the global ecosystem" [58]. Furthermore, the Sustainable Engineering Principles, unlike those of GSE (Tables 2.4), address the social pillar of sustainability (principles 7 and 9). While the Principles do not outline a sustainable design methodology, they can be used with existing design strategies to produce sustainable projects [58]. The importance for engineers to apply the Principles have since been endorsed by the NRC [1].

Table 2.10. Nine Principles of Sustainable Engineering [58].

No.	Sustainability Engineering Principe
1.	Engineer processes and products holistically using system analysis.
2.	Conserve and improve natural ecosystems while protecting human health and well-being.
3.	Use life cycle thinking in all engineering activities.
4.	Ensure that all material and energy inputs and outputs are as inherently safe and begin as possible
5.	Minimize depletion of natural resources.
6.	Strive to prevent waste.
7.	Develop and apply engineering solutions, while considering local circumstances and cultures.
8.	Create engineering solutions beyond current or dominant technologies.
9.	Actively engage communities and stakeholders in development of engineering solutions.

Hannover Principles for Design

The Hannover Principles were developed by McDonough and Braungart [72] to guide engineers who seek to incorporate sustainability into their designs (Table 2.11). The set of nine "maxims" do not outline sustainable design requirements, but rather they describe principles that the designer can employ during decision-making. Like the Nine Principles of Sustainable Engineering, the Hannover Principles consider the social aspects of sustainability and also endorse waste reduction and renewable energy utilization. Furthermore, the Hannover Principles emphasize the responsibility of engineers for the outcomes of their designs (principle 4).

Table 2.11. Hannover Principles[1] for sustainable design [72].

No.	Principle[1]
1.	Insist on human rights and sustainability.
2.	Recognize the interaction of design with the environment.
3.	Consider the social and spiritual aspects of buildings and designed objects.
4.	Be responsible for the effect of design decisions.
5.	Ensure that objects have long-term value.
6.	Eliminate waste and consider the entire life-cycle of designed objects.
7.	Make use of "natural energy flows" such as solar power and its derivatives.
8.	Be humble, and use nature as a model for design.
9.	Share knowledge, strive for continuous improvement, and encourage open communication among stakeholders.

[1]Principles have been simplified from their original formats.

Other Guiding Sustainability Principles

Several other sets of sustainability-related principles may be useful to engineers during the design process [77]. First, the Precautionary Principle may be followed, which states that activities harmful to human life, health, or rights should be avoided, even in the case of scientific uncertainty [78]. The Precautionary Principle was included in *Agenda 21* (Figure 2.1), which states the "scientific uncertainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" [44]. Second, the Earth Charter contains a set of 15 principles intended to aid in societal transition to sustainable development. Endorsed by over 4,500 organizations, the Earth Charter Principles pertain to four themes: (1) respect and care for the community of life, (2) ecological integrity, (3) social and economic justice, and (4) democracy, nonviolence, and peace [79]. Other useful principles include the Bellagio Principles [80] for assessment of sustainability-oriented projects and the Daly Principles [77] for utilization of natural capital.

Sustainable Design Tools

Several tools are available to help engineers engage in sustainable design. Those strategies that may be especially helpful in guiding engineering students in practicing sustainable design thinking, such the use of sustainability indicator frameworks, environmental impact assessments, and strategic design tools are outlined.

Sustainability Indicator Frameworks

Sustainability indicators (Table 2.8) can be used in the design process to compare design alternatives. Since numerous indicators may be available for a given project, the values must be organized into an indicator framework to aid in the engineering decision-making process. Two common indicator frameworks include the Driving forces-Pressure-State-Impact-Response (DPSIR) model and the UN Commission for Sustainable Development (UNCSD) scheme.

1. DPSIR Indicator Framework

The DPSIR framework, developed to categorize indicators for decision-making, was based on several earlier indicator framework models [81]. The earliest was the stress-response model proposed in 1979 by Rapport and Friend to describe the relationship between environmental stresses and policy responses [82]. The Organization for Economic Cooperation and Development later introduced the pressure-state-response (PSR) model in 1994 to indicate that human pressures lead to changes in environmental state, which necessitate societal responses [83]. Finally in 2004, the European Environment Agency introduced the DPSIR model, which added driving forces and impacts to the PSR model [84].

The DPSIR framework is intended to describe the relationships between environmental problems and human activities by identifying indicators as describing driving forces, pressures, states, impacts, or responses (Figure 2.11A). *Driving forces* include root causes of environmental pressures, including human needs for land, housing, and energy. As a result of human demands, *pressures* are exerted on the environment, such as greenhouse gas emissions and water pollution. Human-induced pressures ultimately affect the *state* of the environment, such as air quality, water quality, and resource availability. As pressures cause alterations in the environmental state, impacts on human health, ecosystem vitality, and economic development become evident. With emergence of adverse impacts, society develops and implements a series of *responses*, which can in turn affect each of the framework elements [84-86].

Properly organized DPSIR models can aid in design decision-making. Giupponi [85] proposes that impact indicators describe the problem, while driving forces, pressure, and state indicators relate to the cause of the problem. Remaining response indicators describe the problem solution. By creating DPSIR models for each design alternative, engineers can visualize and quantify how a design (or solution) will impact problem causes. Based on available indicators, the design alternative that is most likely to alleviate the problem can then be selected. Decision makers should remember that DPSIR models describe a limited time frame and that many sustainability indicators are dynamic [85].

2. UNCSD Framework

A framework consisting of themes and subthemes was proposed by the UNCSD to incorporate sustainability indicators into decision-making processes (Figure 2.11B). In the UNCSD model, indicators can describe environmental, social, economic, or institutional dimensions of sustainable development. Within each theme, indicators can refer to a variety of descriptive subthemes (Table 2.12). Suggested indicators for each sub-theme, several of which may be appropriate for design analysis, have been published by UNCSD [87]. For instance, mortality rate and life expectancy are indicators suggested for the health subtheme of the social sustainability dimension, while emissions of greenhouse gasses and consumption of ozone-depleting substances are included as indicators for the atmosphere theme of the environmental sustainability dimension. In addition, indicators such as intensity of material use and economic/human loss due to natural disasters are included as indicators for the economic and institutional categories, respectively. Organization of project sustainability indicators using the UNCSD framework can aid in selecting a design that aligns with overall project goals [70, 87].

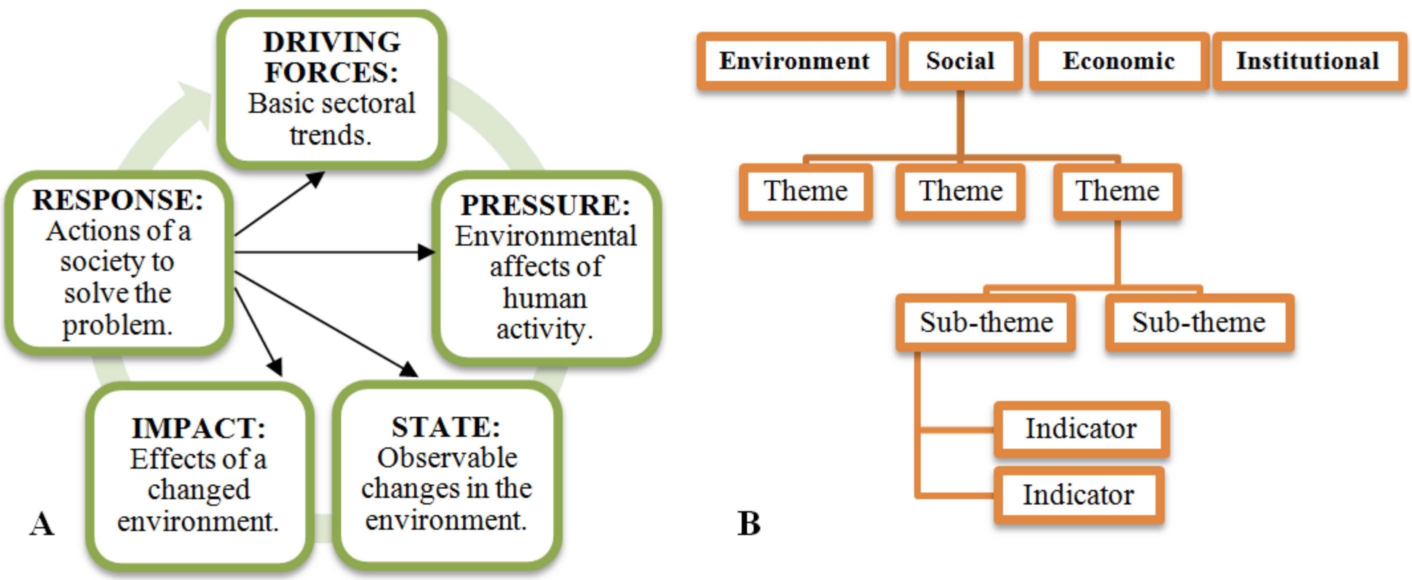

Figure 2.11. Frameworks for organizing sustainability indicators, including the (A) Driving-forces, Pressure, State, Impact, Response (DPSIR) [84] and (B) the UNCSD framework [87].

Table 2.12. Themes and subthemes for use in UNCSD indicator scheme [87].

Economic Dimension		**Institutional Dimension**	
Themes	*Sub-Themes*	*Themes*	*Sub-Themes*
Economic structures	Economic development, trade, finance	Institutional Framework	Strategies for sustainable development, international cooperation
Patterns of Consumption/ Production	Energy use, production and management of waste, transport	Institutional capacity	Access to information, Communications infrastructure, science and technology, Preparation for and aid capacity in natural disasters.
Environmental Dimension		**Social Dimension**	
Themes	*Sub-Themes*	*Themes*	*Sub-Themes*
Atmosphere	Climate change, ozone layer, air quality	Equity	Poverty, gender equality
Land	Agriculture, forests, desertification, urbanization	Health	Nutritional state, mortality, sanitation, drinking water, health benefits
Oceans/Coasts	Coastal areas, fisheries	Education	Educational level, illiteracy
Freshwater	Water quantity, water quality	Housing	Living conditions
Biodiversity	Ecosystems, species	Security	Crime
		Population	Population dynamics

Environmental Impact Assessment Tools

Environmental impact assessment (EIA) tools may be especially useful for engineers to characterize the environmental sustainability of a project. In addition to formal life cycle assessments (LCAs), engineers may also integrate more simplified Materials, Energy, and Toxicity (MET) matrices or Eco-Indicator 99 analyses into the design process.

1. Life Cycle Assessments

LCAs are used to quantitatively characterize the environmental impacts of a product or service over its lifespan. Based on the “product-system,” an LCA analysis is conducted by considering the environmental effects that occur within each of the five stages of a products lifecycle: material acquisition, product production, distribution and transportation, re-use and maintenance, and end-of life disposal [70]. The contribution of each lifecycle phase to environmental degradation, such as carbon emissions or water usage, is calculated and converted to an appropriate functional unit. The final life cycle score is then computed to aid in evaluation of an existing project or development of a project [13, 70]. Completion of LCAs are facilitated by International Organization for Standardization (ISO) guidelines (ISO 14044) and specialized computer software packages [88, 89].

Results from such assessments can provide important insights during the design process. While LCAs are advantageous for engineers because they provide a holistic view of a project’s environmental impacts, their time-intensive nature makes them difficult to conduct during project design. However, if LCA reports are available for competing projects or project components, they can be used to compare design alternatives. When consulting LCAs, it is important for designers to consider the subjective nature of the results, due to selection of system boundaries and data interpretations. Nevertheless, integration of completed LCAs into the design process is a useful method for quantifying project environmental impacts [90].

2. MET Matrix

The MET matrix (Table 2.13) was developed as a tool for design engineers to conduct simplified LCAs. Like expanded LCAs, the MET matrix approach requires designers to consider the environmental impacts that result during five life cycle phases, which span from materials production to product disposal. However, in a MET matrix, environmental impacts are assumed to result only from material cycles, energy use, and toxic emissions. The designer records appropriate qualitative or quantitative information into each of the matrix cells. Comparison of MET matrices from members of a design team can then facilitate the evaluation and improvement of designs. Thus, MET matrices can be used to organize data and concepts related to the environmental impacts of a design project [90, 91].

Table 2.13. Sample MET matrix for a coffee vending machine (Abridged from [90]).

	Materials Cycle (Input and Output)	Energy Use (Input and Output)	Toxic Emissions
1. Production/supply of materials	Copper, Zinc	High energy content of materials	Fire retardants in printed circuit boards
2. In-house production	Metal waste	Process energy	N/A
3. Distribution	N/A	N/A	N/A
4. Utilization			
operation	Plastic cups, filter paper	Inefficient boiler energy use	N/A
servicing	Easily broken parts	Transport of service providers	N/A
5. End of life system			
recovery	No boiler reuse	N/A	N/A
disposal	N/A	N/A	Circuit boards

3. Eco-Indicator 99

Eco-Indicator 99, developed by Pré Consultants, is another tool for completing simplified LCAs during the design process. While traditional LCAs are tedious and time-intensive, Eco-Indicator 99 provides a relatively quick method for quantifying project environmental impacts by providing extensive data sets for converting environmental impacts into eco-points. The designer outlines a list of material and resource amounts (A) required for production (A_P), use (A_U), and disposal (A_D) of a product or service. Next, the eco-indicator value (I) for each element is determined from a list of standard eco-indicators. The number of eco-points (P) for each element and the total number of eco-points are then computed, as per Table 2.14. Projects causing more environmental degradation will yield higher eco-scores [90, 92].

Strategic Design Tools

Strategic design tools, such as the Design Abacus, are aids that allow the design engineer to quickly identify areas of project improvement (Figure 2.12A). The Design Abacus, specifically, is completed by considering impacts made in each of three focal areas: environment, society, and economics. For each focal area, a list of important topics is composed and the best-case and worst-case scenarios are entered under good and bad characteristics, respectively. The project is then subjectively scored on a scale from -2 to +2, which corresponds to the worst-case and best-case scenarios, respectively. Once all scores are recorded on the abacus, a line is drawn to connect each of the scores (Figure 2.12B). In addition, the confidence level for each score should be estimated. Depiction of sustainability performance using Design Abacuses can be used to facilitate group discussions, evaluate design alternatives, or summarize improvements of a re-design [90, 93].

Table 2.14. Application of Eco-Indicator 99 tool to determine the eco-score of a design project[1].

	Amount	Eco-Indicator	Eco-Points
Production			
Production Entry 1	A_{P1}	I_{P1}	$P_{P,1} = A_{P,1} * I_{P,1}$
Production Entry 2	A_{P2}	I_{P2}	$P_{P,2} = A_{P,2} * I_{P,2}$
Production Total			$P_{P,total} = \sum_{i=1}^{2} P_{P,i}$
Use			
Use Entry 1	A_{U1}	I_{U1}	$P_{U,1} = A_{U,1} * I_{U,1}$
Use Entry 2	A_{U2}	I_{U2}	$P_{U,2} = A_{U,2} * I_{U,2}$
Use Total			$P_{U,total} = \sum_{i=1}^{2} P_{U,i}$
Disposal			
Disposal Entry 1	A_{D1}	I_{D1}	$P_{D,1} = A_{D,1} * I_{D,1}$
Disposal Entry 2	A_{D2}	I_{D2}	$P_{D,2} = A_{D,2} * I_{D,2}$
Disposal Total			$P_{D,total} = \sum_{i=1}^{2} P_{D,i}$
ECO-SCORE			$S_{ECO} = \sum_{i=1}^{2} P_{P,i} + \sum_{i=1}^{2} P_{U,i} + \sum_{i=1}^{2} P_{D,i}$

[1]All free materials needed to apply the Eco-Indicator tool are available online [92].

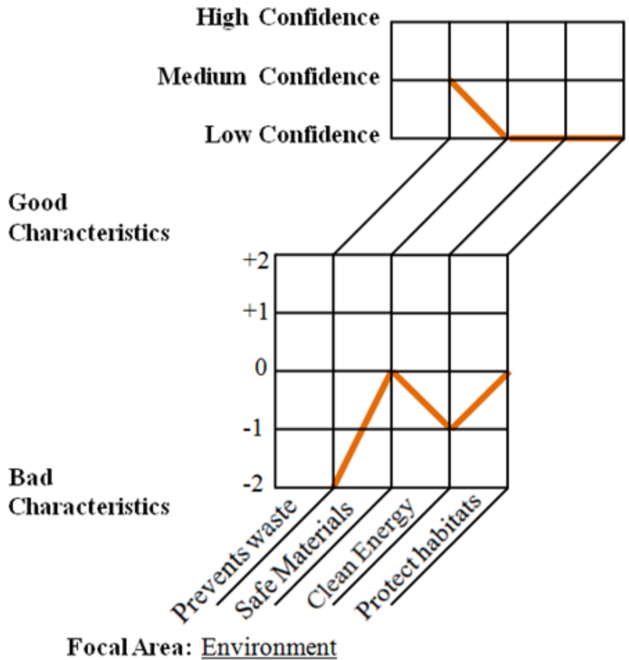

Figure 2.12. Sample design abacuses used in visual depiction of sustainability performance in focal areas [90, 93].

Sustainability Education

Curricular Reform in Engineering

Given the potential impact of sustainable engineering to contribute to a sustainable future, support for reform of undergraduate engineering education to train students to be successful in solving increasingly complex and global problems is growing. Specifically, efforts are needed to update not only the content of engineering curricula, but also the pedagogical strategies that are employed to disseminate this content.

Basis for Curricular Reform

For sustainable engineering to effectively contribute to global sustainability, engineering curricula must be updated to incorporate sustainability-related concepts and skills. Although many higher education institutions have promoted sustainable development, the concept is still considered revolutionary at many universities [94]. Training sustainability-conscious engineers requires emphasis on systems thinking to understand the interconnections between the economic, environmental, and social aspects of design. In contrast, current curricula rely on the "customary reductionist reliance on specialism and testing by repetition" which produces "unbalanced, over-specialized, and mono-disciplinary graduates" [21]. Furthermore, the traditional emphasis on knowledge depth over knowledge breadth will likely render engineers unable to adapt to future conditions where "engineers must be able to design with natural resources that have very different constraints for a wider variety and greater number of end users" [22]. Thus, current engineering curricula must be transformed to properly train future engineers to solve current and future problems in a sustainable manner.

Given the potential for engineers to impact future developments, several organizations have endorsed integration of sustainability into engineering curricula. For instance, the Accreditation Board for Engineering and Technology (ABET) requires that students possess "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context" [95]. Furthermore, the American Association of Engineering Societies (AAES) state in their cannons of professional conduct that "engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties" [96]. In 2010, NSF created an investment area in Science, Engineering, and Education for Sustainability to "promote the research and education needed to address the challenges of creating a sustainable human future" [17]. In 1996, ASCE revised its Code of Ethics to include sustainability principles as part of the canon of civil engineering practices [23]. Other professional organizations, including the Institute of Electrical and Electronics Engineers, the American Society of Mechanical Engineers, and the American Society of Chemical Engineers have endorsed sustainable engineering education [97, 98].

Curricular Content Reform

Methods for Content Reform

Several methodologies and course types have emerged for effective incorporation of sustainability concepts into university curricula. Specifically, four dominant sustainability integration procedures are currently used in higher education (Table 2.15) [95], which employ strategies of horizontal and/or vertical integration. Horizontal integration is a strategy whereby sustainability concepts are incorporated into several courses across a curriculum, while vertical integration is the addition of sustainability courses into an existing curriculum [99]. Many scholars debate whether horizontal or vertical integration is most effective at training sustainability-responsible students; however, preliminary analysis may support superiority of horizontal integration [21, 23, 95]. Whether courses are modified or created to include sustainability concepts, sustainability-related courses include emphasis on one of the three sustainability pillars as a distinct module, while sustainability-focused courses concentrate on the interrelationships between the three sustainability pillars or analyze a topic using a sustainability framework [100].

Table 2.15. Methodologies for incorporating sustainability principles into engineering curricula (Adapted from [95]).

Integration Procedure	Integration Strategy
1. Some coverage of environmental issues and in an existing course.	Neither
2. A specific sustainable development course.	Vertical
3. Sustainable development intertwined as a concept in regular disciplinary courses, tailored to the nature of each specific course.	Horizontal
4. Sustainable development as a possible major or specialization.	Horizontal

Status of Curricular Content Reform in Engineering

Engineering programs across the US have initiated a variety of reform efforts. As part of a study sponsored by the US Environmental Protection Agency, course materials from a variety of engineering disciplines and institutions were examined [101]. Of the approximately 150 courses investigated, only 23% aimed to integrate sustainable engineering concepts into traditional engineering courses (i.e. horizontal integration). In contrast, 77% were vertically integrated, either as having sustainable engineering as the dominant theme (48%), focusing on sustainable technologies for developing sustainable solutions (14%) or being interdisciplinary (co-taught by engineering and non-engineering faculty) (15%). Consequently, vertical integration is the most commonly implemented strategy of curriculum reform within engineering in the US. While it is certainly positive that many institutions are recognizing the need to train sustainability-conscious engineers, the emphasis on vertical integration may promote the misconception that sustainability is to be considered apart from, or as an afterthought of, the design process [102].

Pedagogical Reform in Engineering Education

While a curriculum's content can impact student sustainability learning, the pedagogical approaches that are used to execute a curriculum are also important. While lecture-based instruction dominates in engineering education [103], research has shown that more engaging and student-centered pedagogies more effectively promote student learning [104]. As a result, there have been calls to not only update the content of engineering curricula, but also the teaching and learning techniques used for curricular dissemination [105]. Reviews of student-centered teaching and learning strategies are available [104, 106, 107] and will not be repeated here; rather, the pedagogies and related learning theories applied in this research will be discussed in detail. Specifically, inquiry-based and learning-cycle-based pedagogies, based on constructivist and experiential learning theories, respectively, may be advantageous for facilitating student learning.

Constructivist Theories and Related Pedagogies

1. Constructivist Theories

Constructivist theory proposes that knowledge is constructed by the learner. In contrast to the positivist viewpoint that objective knowledge can simply be transferred from instructor to learner, constructivists postulate that students construct knowledge as they process their own experiences. If experiences align with a student's view of reality, then the new information is assimilated into his or her knowledge framework. However, if an experience contradicts a student's understanding of reality, then the new information may either be ignored or accommodated by altering his or her view of reality. Either through assimilation or accommodation, learning requires that students engage in experiences; thus, constructivist theory holds that learning is an active, experience-driven process [108, 109].

Social constructivist theory suggests that learning is fundamentally dependent on social interactions. While there are differing branches of social constructivism, the emergent or pragmatic perspective describes learning as occurring as students internally construct knowledge through their social interactions within a community [110, 111]. As a result, pragmatic social constructivism posits that learning occurs both individually and in the context of group interactions[112]. As a result, application of social constructivist theory requires that students engage in active learning through collaboration with peers.

2. Inductive and Inquiry-Based Teaching and Learning

Based on constructivist learning theories, inductive teaching requires that a context for learning be presented before introducing fundamental theories and concepts. For instance, examining a case study on sanitation in a developing country may encourage students to engage in a lecture on drinking water treatment. A key feature of inductive teaching strategies is that they promote a student-centered learning environment by encouraging active, collaborative learning. Active learning requires that students assume responsibility for the learning process, while collaborative learning occurs when students learn from their peers. One example of active, collaborative learning is learning-by-teaching where students prepare and deliver concepts to group members. Inductive teaching strategies comply with constructivist theories by providing students with opportunities to engage in experience-driven learning [104, 108].

Inquiry-based teaching is one example of an inductive method that uses problems to provide a context for learning. Several types of inquiry-based teaching can be employed, each of which varies in the level of instruction provided by the teacher. In structured inquiry, students are given a problem and guidelines for how to solve the problem. Alternatively, in guided inquiry, students are provided with a problem but they are required to solve the problem without instructor directions. Open inquiry requires that students both select and solve the problem. Regardless of the inquiry-based teaching strategy chosen, students are encouraged to actively learn by engaging in experiences [108].

Experiential Learning Theory and Related Pedagogies

1. Experiential Learning Theory

Originally proposed by Kolb and based on constructivist theory, experiential learning theory (ELT) is a model for adult development which asserts that experiences play a key role in the learning process. ELT postulates that learning is “the process whereby knowledge is created through the transformation of experience [113].” Thus, learning occurs as students process educational experiences and integrate resulting conclusions into their existing knowledge bases. Furthermore, the ELT model proposes that student learning occurs in two stages: grasping experiences and transforming experiences. Students may grasp or perceive experiences through concrete experience (CE) or abstract conceptualization (AC). Concrete experiences may occur by perceiving information using one’s senses, while AC can include perceiving information through concepts or symbols [114]. Once experiences have been grasped, they are transformed or processed through reflective observation (RO) or active experimentation (AE). Those that reflectively process experiences may do so by contemplating actions of themselves or others, while active processers may begin to immediately experiment with their newly-formed conclusions. Depending on students’ learning styles, they will often use a preferred method for grasping experiences (CE or AC) and transforming experiences (RO or AE) [113, 115].

2. Learning Cycle-Based Instruction

Based on ELT, Kolb postulates that complete learning occurs when students engage in all phases of the learning cycle (Figure 2.13). Based on the methods for concept grasping and transformation, Kolb’s learning cycle consists of four parts: CE, RO, AC, and AE. Learning begins when a student engages in a given experience (CE) and continues as he or she reflects on that experience (RO). Student reflection leads to development of logical conclusions, to which theoretical or expert ideas can be added (AC). Finally, students apply and test new concepts and skills (AE) to develop templates for new experiences (CE) [113, 115]. Often referred to as "teaching around the cycle," Kolb's ELT suggests that an instructor can promote complete learning by designing course materials to encourage students to complete all learning cycle phases (Figure 2.13) [108, 114]. For instance, CE may be facilitated through laboratories or primary text reading, while RO is promoted through journals and brainstorming [116]. Next, AC can occur during lectures or model building, while AE is encouraged through projects and case studies [116]. When "teaching around the cycle," students are encouraged to learn as they are taught using their preferred styles; however, teaching students using less-preferred styles may help them to develop new ways of thinking about problems or ideas [108, 115, 116].

Research on Pedagogy for Sustainability Education

Empirical research concurs that innovative pedagogies are effective for facilitating effective teaching and learning related to sustainability. In fact, expert perceptions of pedagogies for sustainability education were explored by Segalàs, Mulder, & Ferrer-Balas [117] through interviews. Almost all experts (88%) supported project-based learning as the most advantageous "active" strategy for introducing sustainability to students. Even so, many instructors (71%) also supported traditional lecturing as being important for providing students with fundamental information before engaging in active learning. Other popular active pedagogies included use of case studies (41%) and discussions and debates (29%). Overall, experts emphasized the fact that a "multi-pedagogy" approach is needed to reach a variety of students and promote metacognition. Expert beliefs about sustainable education were confirmed in another work by Segalàs and collaborators [118], which showed that student learning about sustainability was improved when experiential and active learning pedagogies were used in the classroom. Thus, student learning about sustainability can be encouraged by providing opportunities for collaborative, student-driven experiences.

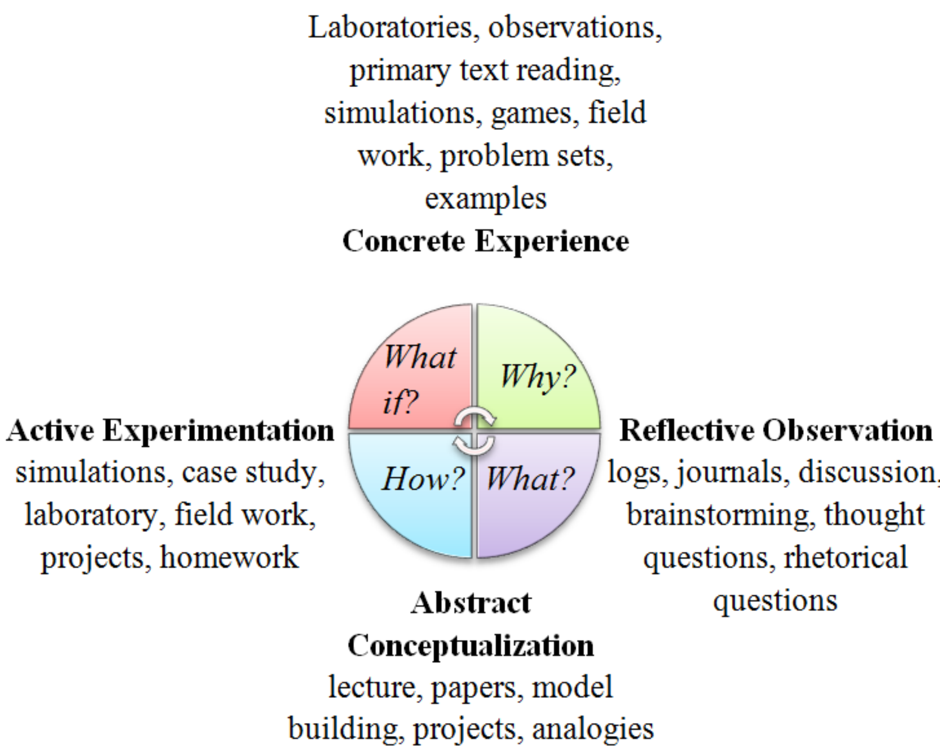

Figure 2.13. Kolb's Learning Cycle and corresponding classroom activities [113, 116].

Sustainability Assessments in Higher Education

While both updating the content addressed and pedagogies employed in engineering classrooms can positively impact sustainability education, assessments are required to ensure that efforts indeed have a positive impact on student learning. Methods are available for both assessing the sustainability content of curricula, as well as for quantifying student sustainability knowledge and design abilities.

Curricular Assessments

Due to growing interest in incorporating sustainability into the university experience, several curricular assessment methods have been proposed. While systematic and widely-used tools are available, some authors have relied on student perceptions to gauge the effectiveness of curricula.

Student Surveys

Since students are intimately familiar with their curricula, they can provide unique insights into the content and quality of courses. As a result, many stakeholders in higher education have relied on student perceptions surveys to examine curricular quality. According to a working group at the University of British Columbia (UBC) in Canada, students (n = 635) showed overwhelming support for integrating sustainability into curricula, with a majority stating that sustainability should be taught in their programs, regardless of degree level or academic unit [119]. Yuan & Zuo [120] examined Chinese students' support of seven dimensions of higher education for sustainable development, including management systems, environmental sustainability, sustainable curricula, research and development, faculty and staff development/rewards, student opportunities, and social responsibility. Results supported that students most emphasized environmental sustainability and least supported sustainable curricula. Overall, while some students were strongly supportive of incorporating sustainability into their coursework, others preferred to rely on alternative factors to promote sustainability.

Systematic Curricular Assessment Tools

A number of more formal and systematic tools for examining sustainability in higher education are also available. For instance, the Auditing Instrument for Sustainable Higher Education [121], the Graphical Assessment for Sustainability in Universities tool [122], and the Environmental Management System Self-Assessment [123] have been presented in the literature. While these tools seek to quantify the sustainability of university operations as a whole, they may or may not include a comprehensive examination of curricula [124].

The Sustainability Tool for Assessing UNiversity's Curricula Holistically (STAUNCH®) overcomes many of the shortcomings of broader institutional assessment systems. Originally developed at the BRASS Research Centre at Cardiff University in the United Kingdom (UK), this tool was designed to not only to systematically analyze the sustainability content of a single curriculum, but also to be feasible for comparing programs within and across institutions. Course descriptors, including course descriptions, syllabi, and/or website materials, are first graded on a four-point scale (Table 3.5) on the extent to which 40 sustainability topics (Table 3.4) from four major themes (economic, environmental, social, and cross-cutting) are addressed. Data are inputted into the proprietary STAUNCH® system, which is licensed by Organisational Sustainability, to yield quantitative metrics (strength and contribution) that can be used to benchmark curricular quality. The STAUNCH® system has been implemented internationally to assess and improve sustainability education, including the nation-wide evaluation of university curricula funded by the Higher Education Funding Council for Wales [21, 125]. Additional information on using STAUNCH® for curricular assessment is provided in *Chapter Three*.

Student Conceptual Knowledge and Awareness Assessments

Need for Sustainability Knowledge Assessments

Effective methods for assessing student sustainability knowledge are needed throughout the process of transforming an undergraduate curriculum or course. First, assessments are needed to characterize students' prior knowledge to properly inform the design of educational interventions. For instance, if students simply have no prior knowledge about sustainability, then strategies are needed to help students "add" sustainability knowledge to their repertoire. If students have accurate but incomplete knowledge of sustainability, then educators can help students "fill the gaps." Both concept "addition" and "gap filling" are forms of knowledge "enrichment." However, the third possibility is that students have misconceptions related to sustainability that must be corrected. In this most extreme case, "conceptual change" is required, which can be relatively difficult for educators to facilitate, depending on the level of misconception. Thus, educational interventions must be designed with students' prior knowledge in mind to determine if knowledge "enrichment" or "conceptual change" should be facilitated. After the intervention has been implemented, assessments are again needed to verify the effectiveness of and continuously improve the instruction. Hence, assessment is critical for designing and evaluating strategies for improving student sustainability knowledge [126-128].

Inadequacies of Traditional Assessment Tools

Traditional assessments may be inadequate for capturing student understanding about sustainability. An ideal assessment task is objective and reliable, minimally influences student responses, and reveals knowledge structure [129]. Traditional assessment instruments, such as multiple choice or standardized tests, inherently restrict student responses and provide little insight into knowledge structure, although they are usually very objective [130]. As a result, objective tests are especially unsuitable for assessing sustainability knowledge because they do not allow students to reflect the inherently broad content and interrelated structure of the sustainability domain. Open-ended assessment methods, such as essays and presentations, are usual alternatives that disclose more about knowledge structure, but are often accompanied by subjective scoring procedures that are difficult to apply [130]. In addition, student inability to produce acceptable artifacts (e.g. reports or posters) may be mistaken for lack of knowledge in the domain [130]. Consequently, traditional open-ended assessments may be unfeasible for broad and accurate sustainability assessments. As a result, many researchers have relied on student perceptions surveys to characterize sustainability knowledge. Others have suggested that more innovative tools, such as concept maps (cmaps), should be used to accurately capturing student knowledge in a complex domains [131].

Student Perceptions Surveys as Knowledge Assessment Tools

Several survey-based studies highlight students' knowledge and awareness of sustainability from across the globe. The results of a survey conducted by Emanuel & Adams [132] of university students from Alabama and Hawaii in (n = 406) show that approximately one-third of students "[did] not know much about sustainability." Earl, Lawrence, Harris, & Stiller [133] found that college students at the College of Charleston knew even less about sustainability, with over half of surveyed participants (*n* = 100) indicating that they "had not heard of the term." Conversely, survey results of Barth & Timm [9] showed that students from Leuphana University in Germany ($n \geq 1000$) demonstrated a "sophisticated" understanding of sustainability, although many students highly emphasized environmental aspects. Even still, of the 1889 students at the University of Plymouth in the UK surveyed by Kagawa [134], only one-third were "very familiar" with the term sustainable development. When participants from the Kagawa [134] study were asked to provide up to four keywords related to sustainable development, greater than 45% were related to the environmental dimension. Bielefeldt [135] also adapted the Kagawa [134] survey to study the sustainability knowledge of CEE students at the University of Colorado (*n* = 344) in the US. More than half of the first-year students were only "slightly" familiar with the term sustainable development, while almost half of seniors were "somewhat familiar." Yuan & Zuo [120] surveyed 1134 students from Shandong University in China where a majority of students indicated that they "[knew] to some extent" about sustainable development. Even still, Tuncer [136] reported that over 90% of surveyed students (*n* = 828) from Middle East Technical University in Turkey agreed with a basic definition of sustainable development, although over half supported environmental protection over economic growth. Overall, it is important to study student conceptions because student knowledge is critical for encouraging sustainable practices on campuses [133].

A number of researchers have also investigated the impacts of demographics and educational experiences on students' knowledge of and awareness of sustainability using surveys. For instance, Earl et al. [133] and Kagawa [134] found that males perceived to be more familiar with sustainability than females, while Tuncer [136] showed females to be more knowledgeable than males. Earl et al. [133] also found that students not originating from the southeast US were more confident in their sustainability knowledge than their peers. Internationally, Barth & Timm [9] found sustainability-related coursework to impact sustainability awareness, since students pursuing a sustainability-related minor or major emphasized the social aspects of sustainability more than their peers only seeking disciplinary specialization. Conversely, Tuncer [136] showed enrollment in an environmentally-focused course to have no impact on sustainability knowledge. In relation to academic standing, Bielefeldt [135] demonstrated that senior CEE students were more familiar with sustainable development than their first-year counterparts.

Concept Maps as Knowledge Assessment Tools

While student surveys are widely reported in the literature for examining student sustainability knowledge, cmaps may provide a more flexible method for capturing students' conceptual understanding of sustainability. Although cmaps are discussed extensively in the literature, including their function and structure, theoretical bases, key components, and reliability and validity, their use in the area of sustainability education is fairly new.

1. Concept Map Function and Structure

Cmaps are graphical tools for organizing knowledge. Construction of a cmap is completed by enclosing concepts related to a central topic in boxes and using connecting lines, as well as linking phrases, to depict relationships between concepts [137]. The basic unit of a cmap is a proposition, which includes two concepts joined by a descriptive linking line. Propositions that include the cmap topic define the map hierarchies, and the level of hierarchy is defined as the number of concepts in the longest path down a hierarchy. Cross-links, which are important for representing connections between concepts, are descriptive linking lines that create propositions by joining two concepts from different cmap hierarchies (Figure 2.14). Cmaps have been used in educational settings as a learning strategy, an instructional method, a curriculum planning guide, and an assessment tool [130, 138].

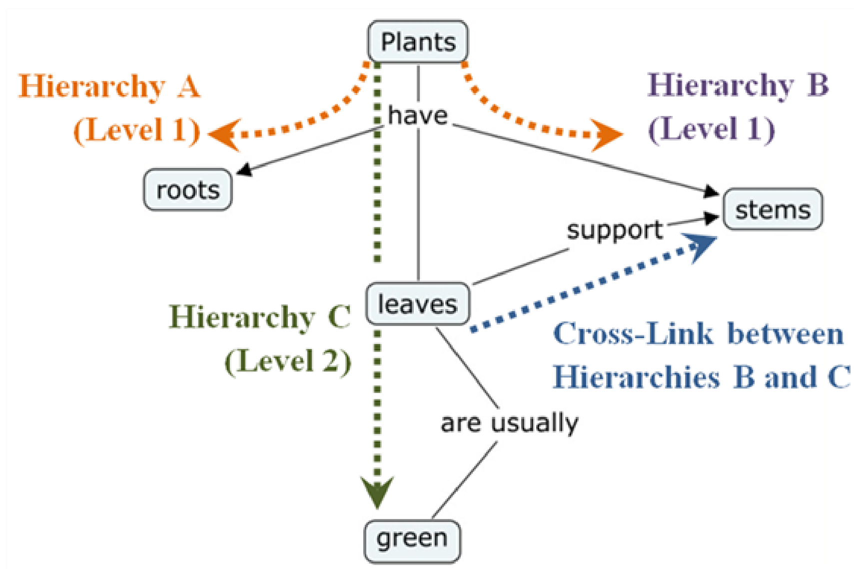

Figure 2.14. Cmap hierarchies and cross-links (Adapted from [137]).

2. Concept Map Theoretical Basis

Use of cmaps is supported by cognitive psychological research in the area of semantic memory theory. Semantic memory refers to an organized database of concept-based knowledge, such as meanings, understandings, and images [139]. Unlike episodic memories, semantic memories contain factual knowledge about the world that is not temporally-dependent [139]. Semantic memory theory posits that knowledge networks are formed by creating directed links between related concepts. Some researchers have proposed that networks are structured hierarchically with broad concept categories being divided into more specific sub-categories (Ausubel's hierarchical memory theory) [140], while other researchers have rejected this assumption (Deese's associationist memory theory) [141, 142]. Nevertheless, interconnectedness within the structure is an important network characteristic, since it increases one's ability to access concepts [138] and is a key feature that differentiates expert and novice knowledge frameworks [143]. Since cmaps mimic the structure of internal semantic networks, student-generated constructs may be used to infer a student's domain understanding [143]. Thus, using cmaps in the classroom can provide students with an opportunity to articulate and evaluate their semantic memory networks, while providing instructors with a tangible construct to aid in evaluation of a particular knowledge domain.

Based on Ausubelian learning theory, or more generally constructivist learning theory [138], integration of cmaps into classroom activities is an effective strategy for encouraging meaningful, rather than rote, learning. As students disseminate and analyze their semantic memory networks, they can visually identify inconsistencies, areas of deficiency, and potential connections between new knowledge and long-standing concepts. In addition, instructors who use concept-map-based assessments provide students with an incentive to engage in meaningful learning, since rote learning would result in poor cmaps and resulting assessment scores [137, 144, 145]. Thus, cmaps provide students with a framework for engaging in, and instructors with a framework for encouraging, meaningful learning.

3. Key Aspects of Concept Map Assessments

Cmaps are an alternative to traditional assessment tools for characterizing knowledge content and structure. Cmap assessments are widely varied, although all include a task, format, and scoring method [143]. The reliability and validity of many concept-map-based assessments are also promising [130, 142].

A. Task Directedness

Concept mapping tasks vary widely depending on the directedness, or level of instructor-dictated constraints. The fill-in-a-map task, in which students produce a cmap by filling in a blank map structure with instructor-provided linking lines, linking words, and concepts, exhibits the highest degree of directedness. In contrast, the construct-a-map task, in which students structure their own maps using original propositions, exhibits the lowest degree of directedness. Intermediate levels of directedness are imposed when students complete the construct-a-map task using instructor-provided linking words and/or concepts. Low-directedness activities require students to engage in higher-level cognitive functions since decisions must be made regarding the structure and content of cmaps. In addition, absence of instructor interference allows students to reveal the structural arrangement of their knowledge, as well as any misconceptions in their knowledge bases. As a result, cmaps from low-directedness tasks can be used to monitor changes in knowledge content and structure over time. However, the wide variations in student cmaps resulting from tasks of low directedness may lead to difficulties in scoring. Thus, the directedness of the cmap assignment can affect cognitive loading, feasibility of time-dependent assessments, and ease of scoring [130, 142, 143].

B. Format

Several formats are available for students to generate cmaps. Most simply, students can transcribe cmaps by hand onto paper [142]. Alternatively, students can use specialized software, which allows them to easily modify cmaps and efficiently organize knowledge for complex domains [142, 146]. CmapTools, developed by the Florida Institute for Human and Machine Cognition, is an example of a free and downloadable software that can be used in educational environments to aid students in cmap generation [146]. Overall, the chosen format depends on the complexity of the knowledge area and the skill level of participants.

C. Scoring Approach

One significant challenge in using cmaps as assessment tools is identification of a robust method for scoring student-generated cmaps [131, 147-149]. Such methods are required for comparing student performance, both between populations and over time. The traditional method can be used to characterize knowledge breadth, depth, and connectedness through quantification of the number of concepts, highest hierarchy, and number of cross-links, respectively (Table 3.7). Alternatively, the holistic method can be applied by using a rubric to rate the comprehensiveness (knowledge breadth and depth), organization (knowledge connectedness), and correctness using a three-point scale (Table 3.8). To further examine the content of sustainability-related cmaps, the categorical approach, which requires classification of each concept according to a ten-category taxonomy, can be employed (Table 3.9). The categorical method provides information on the category that students most associate with the domain, as well as the connectedness between concepts from different categories (CO_j, CO_{cohort}) (Table 3.10). Additional information on cmap scoring methods is also presented in *Chapter Three*.

4. Reliability and Validity

Reliability and validity are important features of assessment tools. Reliability is a measure of the variation in assessment scores that results from errors inherent in the assessment tool. Because of variability in student understanding, scores are expected to vary between individuals; however, variability in cmap scores may also occur due to differences in student abilities to construct cmaps, expert knowledge of judges, and scoring consistency. Validity describes the appropriateness of conclusions made based on assessment scores. A valid cmap assessment results in a product that properly characterizes the content and structure of knowledge, as well as employs a scoring method that adequately extracts this information. Validity can be compromised if the complexity of the concept mapping task hinders students in transcribing their knowledge [130, 142, 150].

Many studies have examined the reliability and validity of cmap-based assessments. Using Generalizability Theory, McClure et al. [130] reported the reliability g-coefficient to be 0.41 for traditional cmap scores generated through a construct-a-map task with 20 instructor-provided concepts. Traditional cmap scores correlated with other measures, which also established concurrent validity. The holistic scoring approach was first validated by Besterfield-Sacre et al. [131], and Borrego et al. [151] later determined the reliability of holistic scores determined by a panel of three inter-disciplinary judges from a construct-a-map task to be marginally acceptable (Cronbach’s alpha = 0.69). The overall cognitive validity of cmaps has also be evaluated in-depth by Ruiz-Primo [143, 150]. More extensive reviews of cmap reliability and validity are available in the literature [130, 142, 150].

5. Appropriateness of Concept Maps for Sustainability Knowledge Assessments

Cmaps overcome many of the shortcomings of traditional assessments, while being especially appropriate for sustainability knowledge. Constructing cmaps allows students to freely reveal both the content and structure of their understanding. As a result, concept-map-based assessment tools are ideal for characterizing broad student conceptions about sustainability, as well as capturing how well they grasp the inherent interrelationships between sustainability dimensions. Additionally, the ability of cmaps to capture both content and structure makes them useful for identifying whether sustainability knowledge is absent, incomplete, or incorrect, and subsequently whether knowledge "enrichment" or "conceptual change" is needed, respectively [126, 127]. Furthermore, cmaps are often more simple to create than essays, presentations, or posters [130], which allows students to focus on their understanding of the material, rather than on development of the construct.

6. Previous Use of Concept Maps for Sustainability Knowledge Assessments

Although a few authors have used cmaps to characterize student sustainability understanding, no study exists that provides a comprehensive analysis of scoring methods for sustainability cmaps. Segalàs et al. [152] investigated the effectiveness of six sustainability courses by comparing 506 student cmaps before and after delivery of several sustainability-related courses using the categorical scoring method [152]. While a significant sample size was used, no measures of interrater reliability for concept categorization were reported, and no other scoring method was used to substantiate categorical metrics. Borrego et al. [151] analyzed cmaps before and after a green engineering course using the holistic scoring method and found that the comprehensiveness, correctness, and organization of student maps increased after course delivery. While internal consistency, which was measured by Cronbach's alpha, was reported for holistic scores, no other method was used to confirm results. In addition, the holistic approach was only applied for 10 cmaps, which fails to demonstrate feasibility for a larger sample size. Use of cmaps as assessment tools has also been suggested for characterizing student understanding of social sustainability in a sustainable construction course, although no corresponding data was reported [153, 154]. Thus, cmaps are beginning to be applied as assessment tools for studying student sustainability knowledge, but additional work is needed to evaluate scoring methods.

Assessment of Student Sustainable Design Capabilities

While it is necessary to quantify students' conceptual understanding of sustainability, it is especially important to be able to examine engineering students' abilities to apply this knowledge during design. Little attention has been dedicated to assessing students' sustainable design capabilities in the literature, although the use of rubrics to examine student design projects may prove to be especially advantageous for characterizing sustainable design skills.

Use of Rubrics in Engineering Education

Rubrics are simply scoring tools that detail the expectations and requirements for an assignment [155]. Specifically, rubrics are advantageous when a "judgment of quality" is required to critique a work, which is often the case for writing samples [155]. More generally, rubrics are used to judge the quality of constructs (e.g. reports, presentations, etc.) made by students during performance tests, which require students to exhibit high-level skills to complete an authentic (i.e. real-world) challenge [156]. As a result, rubrics are commonly used in the classroom as both assessment and teaching tools to enhance student learning [157]. For instance, an instructor may provide students with a rubric to guide them in completion of a design task. Reflecting on the rubric helps students self-assess their own work and provides the instructor with a tool for grading the assignment and providing feedback to the students [157]. Alternatively, rubrics may be used for evaluation purposes to track changes in educational programs over time due to reform efforts [158, 159]. In engineering education, rubrics have been used widely to assess and evaluate many complex skills, including critical thinking [160] and integration of interdisciplinary knowledge [151].

Types of Rubrics

No matter the intended use, rubrics can usually be classified into one of two categories. A holistic rubric is one that requires a judge to make a single, overall judgment about the quality of student work [161]. Alternatively, an analytic rubric includes specific criteria with more than one level of achievement to aid evaluators in scoring quality based on several aspects or components [162]. It has been argued that analytic scoring provides a more objective assessment of construct quality because it minimizes biases that may impact holistic judgments [161]. For examples of holistic versus analytic rubrics, see Ralston & Bays [160].

Developing a Rubric

As summarized by Allen & Tanner [162], one common strategy for creating analytic rubrics is to design each of the rubric components, which include task description, dimensions, scale, and dimension descriptors, in a step-by-step manner [159, 160]. The task description captures the overall purpose of the assignment or task, while the dimensions encompass the individual criteria by which the task will be judged. The scale defines different achievement levels for student performance and may be reflected by numbers (e.g. 1, 2, 3, 4) and descriptors (e.g. exemplary, competent, developing, unacceptable). Finally, the dimension descriptors describe clearly the requirements for meeting each performance level for each criterion. In addition to these four components, it is critical that performance levels for criteria are observable and measureable. In essence, developers must have a "clear picture" of what attaining each performance level for a criterion "looks like [162]."

Potential Frameworks for a Sustainable Design Rubric

Developing a sustainable design rubric requires a set of criteria by which to judge design performance. A number of rating systems are available for quantifying the sustainability of large infrastructure projects, including Leadership in Energy and

Environmental Design (LEED) and Envision^{TM}, which may provide insights for judging student projects. Alternatively, the 9 Principles of Sustainable Engineering may serve as the foundation for an evaluation tool.

LEED encompasses a suite of rating systems developed by the US Green Building Council that can be used to measure the sustainability of a variety of buildings, including homes, schools, and even neighborhoods. The basic concept behind the LEED framework is that projects earn points for meeting green building criteria that fall within five main credit categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. Depending on the project type, points may be required in additional credit categories. Once a specified number of points are earned, then the project can become certified. Buildings earning at least 40 points are considered "certified," while projects earning at least 80 points are "platinum-certified." More information on LEED is available [163, 164].

Envision^{TM}, developed by the Zofnass Program for Sustainable Infrastructure at Harvard University and the Institute for Sustainable Infrastructure, is a newer system that provides a holistic framework for evaluating the sustainability of infrastructure projects. In fact, the rating system evaluates the community, environmental, and economic benefits of projects, which is in alignment with the three sustainability pillars proposed in the Johannesburg Declaration [4]. More specifically, the rating system includes 60 sustainability criteria that comprise five sections: quality of life, leadership, resource allocation, natural world, as well as climate and risk. Like the LEED systems, additional credits can be earned for innovative strategies and technologies. For each criterion, there is a set of metrics, levels of achievement (improved, enhanced, superior, and conserving), and explanations for how to advance in achievement level. For additional details, please consult the Envision^{TM} website [165].

While a number of detailed rating systems are available for guiding sustainable development of civil infrastructure, the Nine Principles of Sustainable Engineering may serve as a more general framework for engaging in sustainable design (Table 2.10). Accordingly, many of the Principles are reflected in both the LEED and Envision™ rating systems. For instance, both systems provide criteria for resource use and allocation, which broadly align with the Principle "minimize depletion of natural resources." In addition, both LEED and Envision™ provide extra points for particularly innovative projects. Indeed, one of the sustainable engineering principles directs engineers to "create engineering solutions beyond current or dominant technologies." Overall, the Nine Principles of Sustainable Engineering provide broad and generalizable guidance for engaging in sustainable design.

Summary

Pertinent literature relevant to sustainable development, sustainable engineering, and sustainability education was presented. Overall, sustainable development was described as development in an economically, environmentally, and socially-responsible manner. Engineers can be especially instrumental in promoting sustainable development by designing projects and systems that balance the impacts to each of the three sustainability dimensions. However, reform of both the content and pedagogy of undergraduate engineering education, verified using appropriate assessment tools, are needed to ensure that engineers are equipped with the knowledge and skills needed to engage in sustainable design.

CHAPTER THREE

RESEARCH METHODOLOGY AND RELATED METHODS

Overview: Methodology, Methods, and Theoretical Perspective

Definitions

Inherent in any research process are the methods, methodology, theoretical perspective, and epistemology (Figure 3.1). The methods are the steps taken to gather information and data related to central research questions. Methodology, however, describes the broader research design that dictates the choice of methods. The theoretical perspective refers to the philosophical position that guides the methodology and provides a foundation for its logic. The chosen theoretical perspective often assumes an epistemology, or theory of knowledge [166, 167].

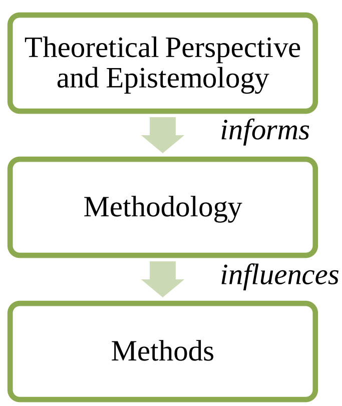

Figure 3.1. Methods, methodology, theoretical perspective, and epistemology in the research process (Derived from [166, 167]).

Case Study Methodology

A case study methodology was selected to assess and improve CEE sustainability education at Georgia Tech. As a methodology, a case study is a detailed investigation of a single occurrence, such as an event, an individual, or a community [167-169]. Positivists often criticize the case study approach because findings are context-specific, non-generalizable, and therefore are not useful for developing theories [167, 170]. However the "concrete" and "context-dependent" characteristics of knowledge derived from case studies actually makes them highly suitable for tackling research questions focused on "the specific application of initiatives or innovations to improve or enhance learning and teaching" [167]. Thus, the case study methodology is appropriate for applied research that aims to verify the efficacy of reforms or interventions.

Research Methods

Quantitative, qualitative, and mixed research methods can be used to conduct engineering education research. Quantitative methods (e.g. surveys) aim to characterize how a set of metrics determine a specific outcome, and are intended to allow researchers to generalize their results to a larger population. Conversely, qualitative methods describe the use of textual data (e.g. open-ended surveys, interviews, observations, etc.) to address research questions within a specific context. Mixed methods, which are employed in the current study, are characterized by collection and analysis of both quantitative and qualitative data in a single investigation. Collected quantitative data in the current study includes student surveys, while qualitative data includes student-generated cmaps. Also, qualitative cmap data is transformed into a set of quantitative metrics in a process coined "quantitizing [171]," which may be considered a mixed-method [172].

Case Study Context: Civil and Environmental Engineering at the Georgia Institute of Technology

Institution and Program Summary

Georgia Tech, founded in 1885, is located in Atlanta, Georgia. The university is comprised of more than 900 full-time faculty and more than 21,500 undergraduate and graduate students. Georgia Tech prides itself in its reputation of outstanding technological research, with $655 million in research expenditures in 2011. As a result, the institution is consistently named as a top public university in the US [173, 174].

The School of CEE, specifically, offers undergraduate bachelor's degrees in civil and environmental engineering. While the Civil Engineering degree has been offered since 1896, the undergraduate Environmental Engineering degree was not offered until 2006 (Figure 3.2). The School is comprised of 54 full-time faculty members and almost 800 undergraduates, with a 15:1 student-to-faculty ratio. During 2011-2012, more than 200 undergraduates obtained degrees in CEE from Georgia Tech [175]. Also, when comparing similar programs from across the country, US News & World Report ranks both CEE programs among the top three [176].

Overview of Civil and Environmental Engineering Curricula

Much of the two undergraduate CEE curricula are very similar. For instance, both civil and environmental engineering students are required to complete fundamental CEE courses (Table 3.1). However, some differences exist (Table 3.2), including the fact that only environmental engineering students are required to complete an organic chemistry class. While civil engineering students must complete at least four of the six CEE breadth electives (Transportation Design, Geotechnical Engineering, Environmental Engineering Systems, Structural Analysis, Construction Engineering, and/or Hydraulic Engineering), environmental engineering students complete two. Both curricula include technical credit hour requirements to allow students to establish specialization [177].

Table 3.1. Courses[1] required for both civil and environmental engineers.

Non-Engineering Courses	Engineering Courses[3]
Calculus I, II, II, Differential Equations	Statics [none]
General Chemistry	Dynamics [none]
General Chemistry	Mechanics of Deformable Bodies [none]
Introductory Physics I, II	Fluid Mechanics [none]
Introductory Physics I, II	Thermodynamics
English Composition I, II	CivE Materials [med]
Economics Requirement	CivE Systems [high]
Electives[2]	EnvE Principles [high]
	Capstone Design [high]
	Computing for Engineers
	Statistics and Applications [none]

[1]91 common credit hours

[2] Policy, Social Sciences, Ethics, Humanities, Other

[3][X] represents extent of sustainability coverage indicated in 2008 ABET Self-Study Report.

Table 3.2. Additional courses[1,2] required for civil and environmental engineers.

Civil	Environmental
Engr Graphics and Visualization [none]	Survey of Organic Chemistry
Biological Principles or Earth Processes	Biological Principles and Earth Processes
Four Breadth Electives: Transportation Design [high], Geotechnical Engr. [none], EnvE Systems [high], Structural Analysis [none], Construction Engr. [high], or Hydraulic Engr. [none]	Additional CEE Requirements: Hydraulic Engineering [none], Environmental Engineering Systems [high], Environmental Engineering Lab [low]
Nine CEE Technical Electives	Nine EnvE Technical/Design Electives

[1]35 and 36 additional credit hours for civil and environmental engineering students, respectively.

[2][X] represents extent of sustainability coverage provided by instructors in 2008 ABET Self-Study Report.

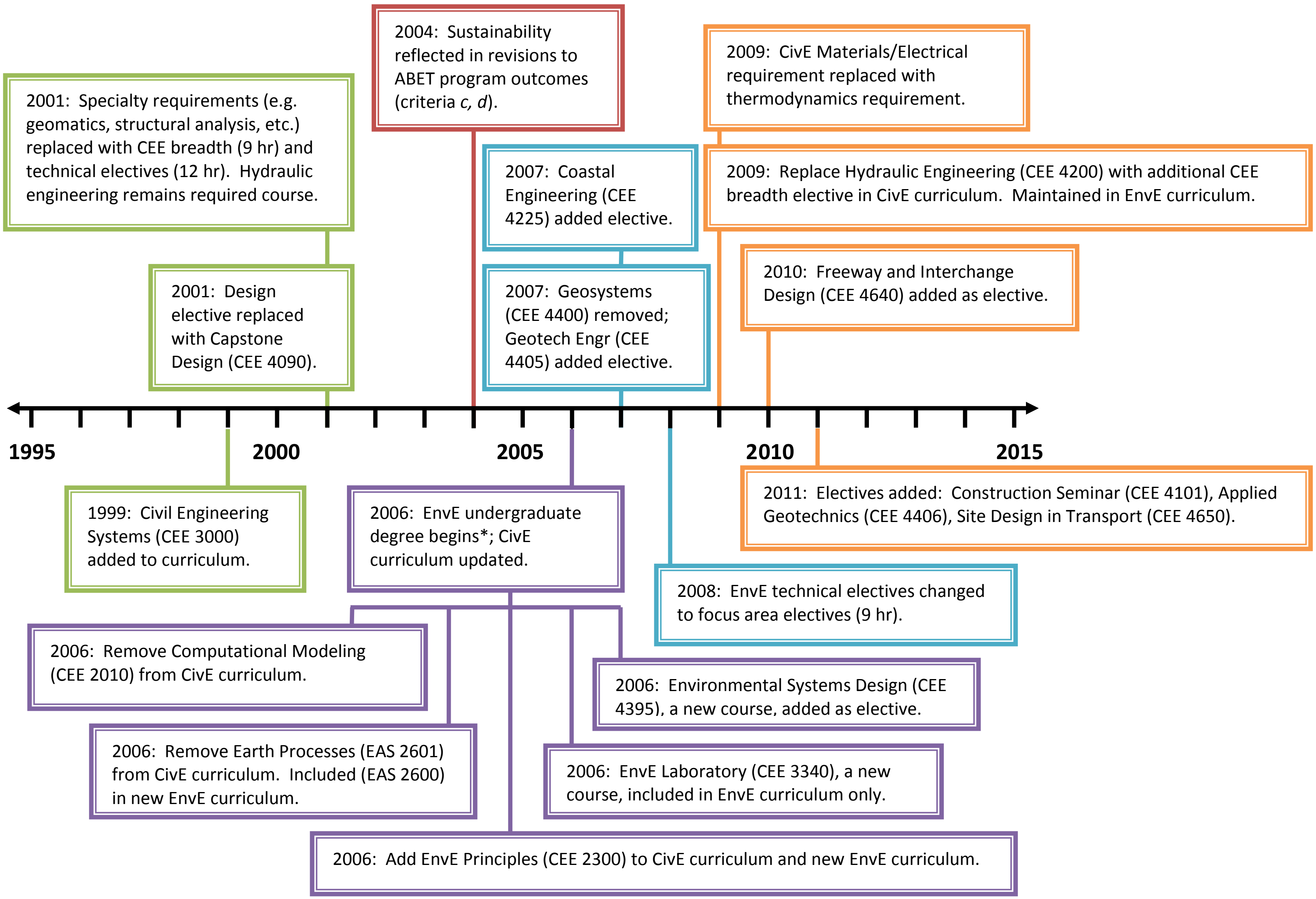

Figure 3.2. Evolution of CEE curricula (compiled based on course catalogs from 1999 - 2012).

Sustainability Education

The School of CEE at Georgia Tech recognized early the importance of training students to understand and apply sustainability concepts, with efforts to incorporate sustainability into the undergraduate curriculum pre-dating the 2004-2005 ABET mandates (Figure 3.2) [178]. Specifically, CEE has implemented both vertical and horizontal integration strategies.

<u>Vertical Integration</u>

Two sustainability-focused courses have been vertically integrated into the CEE curriculum at Georgia Tech (See Appendix A for syllabi). First, Civil Engineering Systems (CEE 3000) was created in 1999 in response to a university-wide sustainability initiative [179, 180]. Required for all CEE undergraduates, CEE 3000 is intended to introduce students to sustainability from a systems perspective. In addition to participating in lectures related to sustainability, students are required to complete a final project that requires a sustainability analysis of an existing civil infrastructure system (see section below entitled “Key Courses” for more details). More recently, a new elective entitled Sustainable Engineering (CEE 4803/8813) was created for interested students to further enrich their knowledge of sustainability. Topics include industrial ecology, earth systems engineering and management, integration of environmental/social/economic issues, life cycle assessment, and material flow analysis. Students also collaboratively work to apply class principles to a problem of interest. The CEE curriculum exposes all students to sustainability, while providing opportunities for motivated students to engage in more in-depth learning.

<u>Horizontal Integration</u>

Many instructors have also sought to integrate sustainability into their own courses. In a 2008 Self-Study Report prepared for ABET, faculty were asked to indicate the contribution of their courses to providing students with "a broad education and knowledge of contemporary issues necessary to understand the impact of civil engineering solutions in a global, social, and environmental context" [181]. Instructors from over 15 of the 37 courses suggested that their courses provided a "high" contribution to sustainability education. Examples of courses whose instructors indicated a "high" level of sustainability content include Environmental Engineering Principles (CEE 2300), Civil Engineering Systems (CEE 3000), and Capstone Design (CEE 4090) (Tables 3.1-3.2) [181]. Since evaluations were made by the instructors themselves, without a requirement to provide any evidence of how sustainability was actually addressed by their courses, additional efforts are needed to examine the quality of CEE sustainability education.

Key Courses

While this case study examines CEE sustainability education as a whole, efforts were made to improve student sustainability learning in two specific courses: Civil Engineering Systems and Capstone Design. Civil Engineering Systems is intended to be completed during the sophomore year [182], although many students take the course later in their programs since it is not a required prerequisite for other courses. Conversely, students complete Capstone Design during their senior years, since core courses must be passed before enrollment.

<u>Cornerstone Design (CEE 3000: Civil Engineering Systems)</u>

Civil Engineering Systems provides students with the fundamentals to engage in sustainable design. The course includes three modules: (1) Systems and Sustainability Perspectives, (2) Systems Performance Analysis, and (3) Economic Decision-Making Tools and Project Evaluation. In the first module, students are exposed to the three-pillars framework for sustainability, including introduction to the Sustainability Venn Diagram and the Nested Dependencies Model (Figure 2.3). In the second module, students learn to examine engineering projects from a systems perspective through identification of a system's purpose, boundaries, components, functional characteristics, linkages (economic, environmental, social), and performance measures. The third module prompts students to examine economic tools that can be used to promote sustainability, such as cost-benefit analyses. Throughout the semester, students complete a sustainability analysis of an existing infrastructure system, which requires them to apply concepts from each of the three course modules. Civil Engineering Systems can be considered to be a cornerstone design course because it provides students with the introductory knowledge and skills to engage in sustainable design [179, 180]. For more information on Civil Engineering Systems, see Appendix A.

Capstone Design (CEE 4090: Capstone Design)

After students have completed core CEE courses, they are required to participate in a capstone design experience (See Appendix A for course syllabus). First, students form "companies" by self-organizing into groups of 4-5 students. Students may create specialized companies by joining with students from similar concentrations (construction, environmental, geotechnical, structures, transportation, or water resources), or create a general civil engineering firm by including students from multiple concentrations.

Within the first three weeks of class, students compile and submit a statement of qualifications (SOQ) in response to a real request for qualifications (RFQ). For example, one semester students prepared SOQs in response to an RFQ from Barrow County, GA for preliminary and final design of a local bypass. Completion of the SOQ assignment is intended to encourage groups to quickly learn about the expertise of group members and overall group dynamics. SOQs are evaluated and ranked using an ordinal system by industry representatives and faculty members. Student companies are then allowed to select capstone projects in the order that their SOQs were ranked.

Student companies may select from a variety of authentic projects provided by design firms, industries, and government agencies. Past sponsors include Jacobs Engineering, the LPA Group, Georgia Department of Transportation, FedEx, Kimley-Horn and Associates, and the Gwinnett County Department of Water Resources. Typical projects include design and/or modification of bridges, roadways, wastewater treatment plants, multi-use paths, and stormwater management systems. After selecting a project, students meet with the project sponsor to discuss project goals and expectations. Throughout the semester, companies meet regularly with project sponsors and a faculty mentor. At the end of the semester, companies present final projects to sponsors, faculty, and classmates. Final grades are determined by faculty and sponsor panels.

Project Overview

A research study was conducted to provide guidance for educating civil and environmental engineering (CEE) students about sustainability. Using the School of CEE at Georgia Tech as a case study, the broad research goals were to assess and improve sustainability education through three different phases of inquiry: (1) benchmarking the current status of CEE sustainability education, (2) using insights from curricular and student knowledge assessments to design a sustainability module to guide students in learning about and applying sustainability concepts, and (3) assessing the impacts of integrating the sustainability module into CEE courses on student learning. Several research questions were outlined for each phase of inquiry (Figure 3.3).

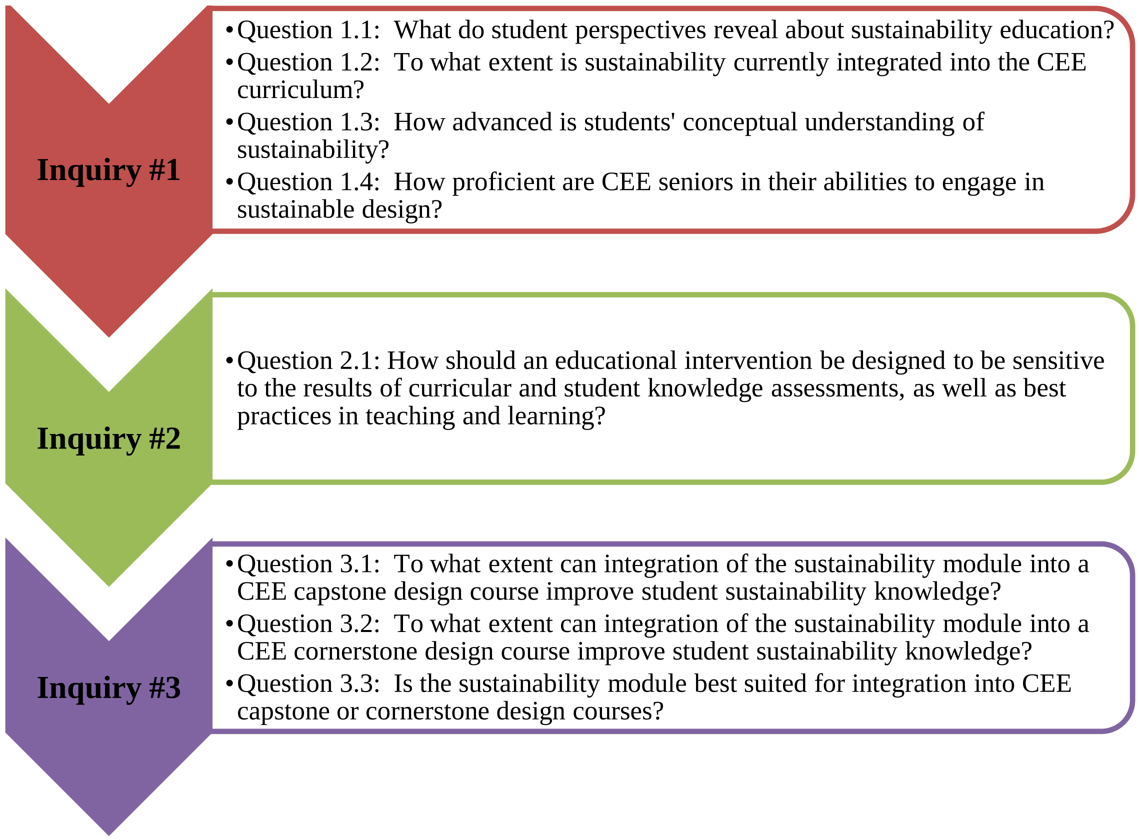

Figure 3.3. Research questions addressed to assess and improve CEE sustainability education.

General Statistical Tools and Methods

Statistics Software

Unless otherwise noted, all statistical computations were completed using IBM's Statistical Package for the Social Sciences (SPSS) (Version 20). Additional information about IBM SPSS is available on the product website [183].

Interrater Reliability

Interrater reliability, which quantifies the extent of agreement between judges, can be quantified using a variety of statistics. Cohen's (unweighted) kappa is one of the most commonly-used metrics for interrater reliability, even though it is intended for the case of two judges generating nominal data [184]. Krippendorff's alpha, an alternative interrater reliability measure, can be applied to all levels of measurements and any number of judges [185]. Krippendorff argues that reliability statistics above 0.80 are adequately acceptable, while values above 0.67 are acceptable for exploratory research [185, 186]. Due to its flexibility and conservative benchmarking scale, Krippendorff's alpha was used extensively in the current work.

Inferential Statistical Tests

Based on Level of Measurement

A variety of inferential statistical tests were used throughout this research study, depending partly on the data's level of measurement (Table 3.3). Nominal variables are usually designated by named categories, while ordinal data are typically organized based on ordered categories [187]. Interval data is the same as ordinal data, except that the intervals between values are equal [187]. Ratio data is simply interval data with a meaningful zero point [187]. Pearson's Chi-Square tests were used to detect differences among categorical dependent variables based on categorical independent variables. For the case of a categorical independent variable and a continuous dependent variable, an appropriate Analysis of Variance (ANOVA) test (either one-way or repeated measures) was used to detect significant differences. Finally, regression analyses were used for data sets with continuous dependent and independent variables. For more information on choice of statistical tests, consult available textbooks [188].

Table 3.3. Choice of inferential statistical test based on the level of measurements[1] of the independent (IV) and dependent variables (DV).

	Discrete[2] DV	Continuous[3] DV
Categorical[3] IV	Chi-Square	*t*-test, ANOVA
Continuous[3] IV	Discriminant Analysis	Regression

[1]More extensive tables, such as those considering multiple IV and DV, are presented elsewhere (e.g. [189])
[2]Discrete variables: nominal, possibly ordinal.
[3]Continuous variables: interval, ratio, possibly ordinal.

Inferential Tests Based on the General Linear Model

Fundamental Assumptions

Statistical tests that rely on the general linear model (GLM), which were used extensively throughout this study (e.g. *t*-tests, ANOVAs, and linear regression), are based on several fundamental assumptions. Foremost, observations are random and independent samples from the populations ("assumption of independence"). If this assumption is violated, there is an increased chance of a Type I error, or a "false positive" in which the researcher declares a relationship that the data does not support [189, 190].

Second, the GLM requires that dependent variables follow a normal distribution ("assumption of normality"). Fortunately, *t*-tests and ANOVAs are robust against violations to the normality assumption, since deviations from normality usually lead to little or no difference in Type I error rates [189, 190]. However, if data is severely platykurtic, then there is an increased chance of a Type II error, or a "false negative" in which the researcher fails to identify a significant relationship indeed exists [189].

Use of ANOVA, specifically, assumes that the population distributions have equal variances ("assumption of homogeneity of variance"). Violating the equal variances assumption is potentially more "damaging" than not meeting the normality assumption because the probability of a "false positive" can be substantially increased. Likelihood of a Type I error increases especially for the case of unbalanced sample sizes [190].

For linear regressions and repeated-measures ANOVAs, linearity of continuous variables is also assumed. This is generally a good assumption, unless there is "strong" theory in support of a non-linear relationship. The outcome of non-linearity, like the violation of normality, is decreased statistical power. Overall, when relying on the GLM, it is important to consider the fundamental, assumptions, especially those that may liberally support false conclusions [189].

Verifying Assumptions

Each of the above assumptions was considered when employing inferential tests based on the GLM. Foremost, data were composed of independent observations, except in the case of experimental designs in which a sample of students were assessed twice. In the latter case, paired-samples *t*-tests or repeated-measures ANOVA tests were used to account for the "nested" structure of the data [189].

Second, the normality of all data was examined using the Shapiro-Wilks test, which is a conservative estimate of normality [191]. Since GLM methods are generally robust against violations to the normality assumption, solely failing the Shapiro-Wilks test did not result in elimination of ANOVAs and *t*-tests. Rather, non-normal data was examined for evidence of severe platykurtosis, which can substantially increase the Type II error rate [189]. No data presented in this work demonstrated severe platykurtosis, indicated by kurtosis *Z*-scores (kurtosis/kurtosis standard error) of less than -3.29 [192], unless otherwise noted. Non-normal data with severe platykurtosis was analyzed using non-parametric methods (e.g. Kruskal-Wallis test or Wilcoxon signed-rank test), which do not rely on the normality assumption.

For ANOVAs, special attention was paid to the homogeneity of variance assumption, since violations can result in non-conservative Type I errors. Specifically, the equal variances assumption was verified using Levene's test. For data that failed Levene's test, Welch's test [189, 190], which does not require equal variances, was employed (when applicable) to verify any significant relationships.

Pearson's Chi-Square Test

Chi-Square tests were used to detect significant trends in categorical data. Like GLM tests, Chi-Square tests assume that the data is composed of independent observations. In the case that students were assessed more than once (matched-pairs), McNemar's Test was used [184]. Second, frequencies within contingency tables should be greater than five. This assumption was met for most data in this work, although Yates correction was applied for any violations [193].

Curricular and Knowledge Assessment Tools

STAUNCH® System for Curricular Assessment

STAUNCH® was selected to assess the quality of and sustainability content of the CEE curriculum (see *Chapter Two* for more details). Not only was STAUNCH® found to be the only tool for specifically examining curricular sustainability focus, but its use has been documented for a variety of institutions and programs [21, 125].   Curricular evaluation using STAUNCH® includes three major phases: (1) data collection, (2) descriptor scoring, and (3) data input and analysis (Figure 3.4) [21, 94].

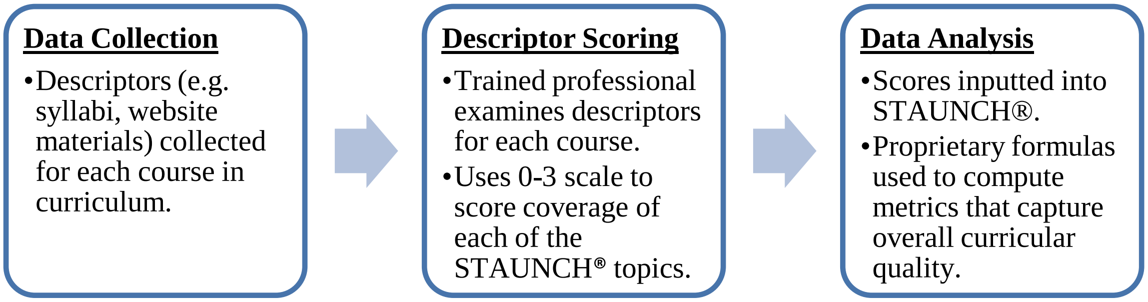

Figure 3.4. Method for completing a STAUNCH® analysis (Adapted from [21, 94]).

<u>Data Collection</u>

Completion of a STAUNCH® analysis first requires collection of descriptors for all courses in a curriculum. Course descriptors may include course descriptions, syllabi, websites, and other materials. The validity of STAUNCH® results relies on the accuracy and comprehensiveness of these obtained descriptors. Sustainability aspects included in the documents but not discussed in class will falsely increase metrics, while topics covered in class but not included in the syllabus will decrease metrics [21, 94, 194].

<u>Descriptor Scoring</u>

Descriptor(s) for each course are next scored by a trained professional. Either a representative from Organisational Sustainability can evaluate the descriptors or an individual can be trained to analyze materials. Evaluation first requires that descriptors for each course be examined for evidence of coverage of 40 sustainability topics, which comprise economic, environmental, social, and cross-cutting dimensions (Table 3.4). For each of the 40 key topics, evidence of coverage is scored using a four-point scale, which ranges from absence of to extensive evidence of topic coverage in the course (Table 3.5). Consequently, a set of 40 scores is generated for each course [21, 94].

Table 3.4. Key topics organized by sustainability theme [125].

Economic	Environmental
Accountability	Alternatives: energy, technologies
Developmental economics	Biodiversity
Finances	Global warming, emissions, acid rain, ozone
GNP/Productivity/Profitability	Land use
Markets/commerce/trade	Policy/administration
Production/consumption patterns	Pollution/accumulation of toxic waste
Resource use/exhaustion	Products and services
	Resource efficiency/eco-efficiency
	Resource Use: depletion, conservation
Social	**Cross-Cutting**
Bribery/corruption	Communication/reporting
Culture and religion	Disciplinarity
Demography/population	Ethics/philosophy
Diversity and social cohesion	Governance
Education and training	Holistic thinking
Employment/unemployment	Long term thinking
Equity/justice	Limits to growth
Health	Responsibility
Labor/human rights	Sustainable development statement
Peace and security	Systems thinking/application
Politics	Transparency
Poverty	
Work/life balance	

Table 3.5. STAUNCH® grading rubric [125].

Score = 0	Score = 1	Score = 2	Score = 3
The issue is not mentioned.	Issue is mentioned, but no explanation given on how addressed.	Issue mentioned with brief description on how addressed.	Comprehensive, extensive explanation on how issue addressed.
Disciplinarity: Courses offered only to one degree (mono-disciplinary)	Disciplinarity: Courses offered in one school in different degrees (multi-disciplinary)	Disciplinarity: Courses offered in another school (inter-disciplinarity)	Disciplinarity: Courses offered in two or more other schools (trans-disciplinary)

Data Analysis

After all descriptors are scored, data is inputted into the proprietary STAUNCH® software. Several key findings are included in the final STAUNCH® report (Figure 3.5), but the contribution and strength metrics are integral for inferring the quality of a curriculum. The strength metric, computed as the weighted average of scores from all courses, captures the *extent* of sustainability coverage. A curriculum receiving mostly scores of three will have high strengths, while those earning mostly ones will have low strengths. The contribution metric considers the *balance* between the four sustainability dimensions. A curriculum that neglects or over-emphasizes dimensions will yield a lower contribution than one that provides balance between dimensions. A set of STAUNCH®-prescribed benchmarks aids in judging the overall quality of a curriculum based on strength and contribution metrics (Table 3.6).

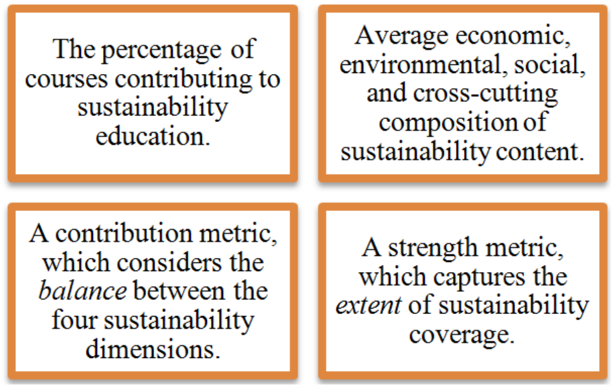

Figure 3.5. Quantitative STAUNCH® metrics used to evaluate sustainability content of a curriculum. Compiled from [21, 94, 124].

Table 3.6. Benchmarks for contribution and strength metrics.

Contribution		Strength	
Range	Classification	Range	Classification
0	none	0	none
0.01 – 0.67	very low	1.00 – 1.29	low
0.68 – 1.29	low	1.30 – 1.49	medium
1.30 – 1.99	medium	1.50 – 1.99	high
2.00 – 3.50	high	> 2.00	very high
> 3.50	very high		

Concept Maps for Conceptual Sustainability Knowledge Assessment

Cmaps were used to analyze student knowledge related to sustainability. While cmaps have been widely applied as assessments in science education [130], they have only recently been suggested for capturing sustainability understanding [151, 152]. Cmap assessments included (1) eliciting students to complete cmaps during an in-class workshop, (2) evaluating cmaps using several scoring approaches, and (3) analyzing cmap scores using statistical analyses (Figure 3.6).

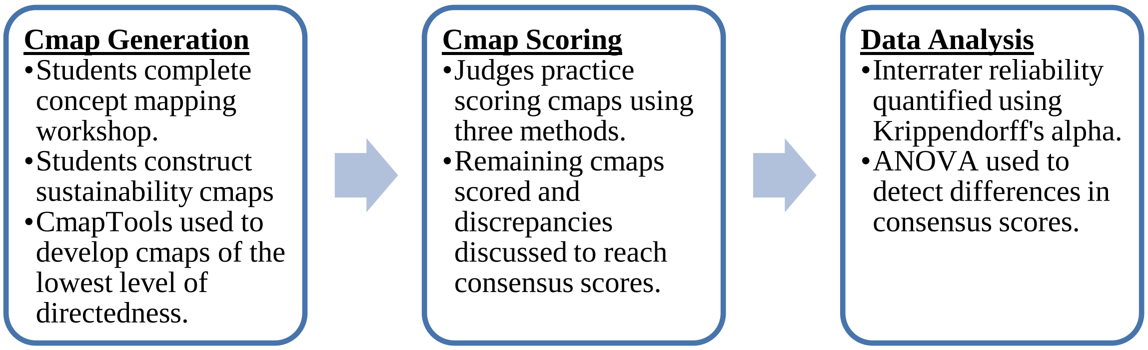

Figure 3.6. Method for conducting concept-map-based sustainability knowledge assessments (Compiled from [131, 138, 151]).

<u>Concept Map Generation</u>

Concept Map Training Session

Before completion of the sustainability concept mapping task, students participated in a 45 minute concept mapping workshop. First, a course assistant gave a detailed presentation on the purpose and construction of cmaps, with emphasis on the key components of cmaps (focus question, concepts, descriptive linking lines, propositions, and cross-links). Examples of well-organized and poorly-organized cmaps were displayed to aid students in understanding the importance of cmap structure. Next, a method for creating cmaps, based on previously published procedures [131, 145, 151, 195], was outlined. Afterward, a demonstration of how to construct cmaps using

CmapTools was completed. Finally, students were asked to create a practice cmap [131, 151] using CmapTools on the focus question: "What are French fries?" All practice cmaps were submitted to ensure student proficiency in creation of cmaps using CmapTools. Precautions were taken to minimize student misunderstanding of cmap construction or use of CmapTools, which could hinder student cmap construction and limit the validity of the sustainability-related cmap assignment.

Concept Map Task and Format

After students were trained to construct cmaps using CmapTools, they were asked to create a cmap on the focus question: "What is sustainability?" The task was designed to be the lowest level of directedness [118, 143], with no concepts or structure being provided. A computer-based format was dictated because it allows students to make many changes to their cmaps, while still producing a final product that can be easily deciphered. Students were not allowed to use any outside sources during cmap creation, although guidelines for cmap construction [131, 145, 151, 195] and instructions for using CmapTools were provided, as suggested by other authors [131, 151]. Final sustainability cmaps were submitted by the students for examination.

<u>Concept Map Scoring</u>

Qualified Judges

Two judges analyzed student cmaps to extract information about student sustainability understanding. One judge was a PhD student in CEE, while the second judge held a graduate degree in Electrical and Computer Engineering. Both judges had completed sustainability-related courses, conducted sustainability-related research, and had been involved with Engineers without Borders (EWB), an organization dedicated to implementing sustainable engineering projects worldwide. In addition, both experts extensively reviewed recent publications related to sustainability and sustainability education prior to scoring student cmaps.

Scoring Methods

Three methods were used to systematically examine student sustainability cmaps. The traditional and holistic methods were chosen to analyze the breadth, depth, and connectedness of cmaps. Since traditional and holistic approaches provide limited information on the content of student knowledge, the categorical approach (Table 3.10) was also used to provide more detail on the categories that students most associate with sustainability.

A. Traditional Scoring Method

The traditional scoring method [131] was used to examine cmaps at a component-level. Specifically, the number of concepts (NC), the highest level of hierarchy (HH), and the number of cross-links (NCL) were quantified to determine sub-scores for knowledge breadth, depth, and connectedness, respectively (Table 3.7). Based on the work of Novak and Gowin [145], the total traditional score was computed by awarding each proposition and example 1 point, each level of hierarchy 5 points, and each cross-link 10 points. The overall cmap score was then computed as the sum of sub-scores. However, since Markham et al. [196] argue that component sub-scores are more valuable when analyzed independently, both total and sub-scores were analyzed to make overall judgments about cmap quality. Overall, component-level scoring was employed as an objective method for quantitatively scoring cmaps.

B. Holistic Scoring Method

As an alternative to analyzing individual components, the cmap as a whole was evaluated using the holistic method (Table 3.8). Based on the rubric first developed by Besterfield-Sacre et al. [131], cmaps were evaluated using a three-point scale to rate the comprehensiveness, organization, and correctness of cmaps. In analyzing comprehensiveness, judges considered the variety of topics (knowledge breadth) and also how extensively topics were covered (knowledge depth). Scoring the organizational dimension required evaluation of the cmap structure, especially the links within and between hierarchies (knowledge connectedness). Unlike the traditional method, the holistic approach included assignment of a correctness sub-score, which characterized the overall appropriateness of propositions and concept placements. Finally, the total cmap score was computed by simply adding the three sub-scores. While evaluating cmaps from a holistic perspective may be more time consuming, it was used to supplement the traditional method and provide a more complete analysis of student understanding.

C. Categorical Scoring

The categorical scoring method is an alternative to the traditional and holistic methods that was developed by Segalàs [152] specifically for sustainability-related cmaps. To apply this scoring routine, each concept in a cmap was categorized according to ten categories: environment, natural resources, social impacts, values, temporal aspects, spatial aspects, technology, economy, education, and stakeholders (Table 3.9). Next, the number of inter-links (NIL), or connections between concepts from different categories, was quantified. As per Segalàs et al. [152], the category relevance (CR) for each category was computed to identify the domain(s) that students most associate with sustainability, while the complexity index (CO_{cohort}) was used to characterize the coverage and connectedness of concepts from different categories (Table 3.10). The Segalàs et al. [152] metrics, which produce summary values for a cohort of students, was adapted to capture the quality of individual cmaps. Specifically, the category distribution (CD) was used to analyze the extent to which a single student associates a specific domain with sustainability, while the student-specific complexity index (CO_j) was devised to characterize the overall coverage of and connectedness of concepts among the ten sustainability categories (Table 3.10). Thus, like the traditional and holistic methods, the categorical approach analyzes of the content and structure of cmaps; however, the categorical approach provides especially detailed information on the specific content included in cmaps [152, 197].

Table 3.7. Rubric for traditional cmap scoring approach [131].

Knowledge Breadth	Knowledge Depth	Knowledge Connectedness
• The number of concepts included in the cmap is counted. • No consideration given to quality or correctness of concepts.	• The number of hierarchies included in the cmap is counted. • The highest level of hierarchy is recorded.	• The number of cross-links, which create propositions using concepts from different hierarchies, is counted. • No consideration generally given to quality or correctness of cross-links.

Table 3.8. Rubric for holistic cmap scoring approach (Modified from Besterfield-Sacre et al. [131]).

	Score = 1	Score = 2	Score = 3
Compre-hensiveness	• Breadth: Map lacks subject definition. Demonstrated by inclusion of only 1 major[1] dimension. • Depth: Knowledge is very simple or limited and barely covers some qualities of the subject area. Demonstrated by sufficient detail provided for only one major dimension.	• Breadth: Map has adequate subject definition, but knowledge is limited in some areas. Demonstrated by inclusion of more than one major dimension. • Depth: Map suggests a somewhat narrow understanding of the subject matter. Demonstrated by lack of detail in 1-3 major dimensions. For the case of lacking detail in 1 required dimension, no or insufficient detail provided for advanced[2] dimensions.	• Breadth: Map completely defines the subject area, with content lacking in no more than one extension area. Demonstrated by inclusion of at least 3 major dimensions. • Depth: Content demonstrates extensive understanding of the subject matter. Demonstrated by sufficient detail in all 4 major dimensions, or detail in 3 major dimensions and at least 1 advanced dimension.
Organization	• Map arranged with concepts only linearly connected. • Few (or no) connections within/between branches[3]. • Concepts not well integrated.	• Map has adequate organization with some within/between branch connections. • Some, but not complete, integration of branches is apparent. A few feedback loops may exist.	• Map is well-organized with concept integration (requires that no concept appears twice). Demonstrated by extensive connections between/within branches. • Sophisticated branch structure and connectivity. Demonstrated by cross-links and possible feedback loops.
Correctness	• Map is naïve and contains misconceptions about the subject area. • Inappropriate terms used. • Inaccurate understanding of certain subject matter.	• Map has few subject matter inaccuracies. • Most links are correct.	• Map integrates concepts properly. • Reflects an accurate understanding of subject matter. • Few or no misconceptions.

[1]Major dimensions: economic, environmental/natural resources, social, and temporal (requires inclusion of present and future considerations) [152].
[2]Advanced dimensions: values, spatial imbalances, technology, education, actors and stakeholders [152].[3]Branches are equivalent to hierarchies.

Table 3.9. Examples of concept categorization based on ten sustainability categories (Adapted from Coral [197] and Segalàs et al. [118]).

Category[1]	Examples
Environment	• pollution, degradation, conservation (of wildlife), biodiversity, ecological footprint, green/clean
Resource (scarcity)	• renewably/non-renewable resources, run out of materials, energy, food, water
Social Impact	• quality of life, health, risk management, shelter
Values	• ethics, awareness, respect for traditions, judgments about sustainability
Temporal	• future generations, scenario analysis, forecasting, backcasting
Spatial Unbalances	• equity, fair distribution of goods, fair use of resources, needs of developing countries
Technology	• best available technologies, industry, efficiency, clean-technologies, impact of technology, technological efficiency
Economy	• role of economy, fair trade, consumption, economic efficiency
Education	• role of education, rise of awareness, educational institutions
Actors and Stakeholders	• role of governments, rules, laws, international agreements, politics, individuals and society

[1]Analysis in the current study was also conducted based on mega-categories. The environmental mega-category was composed of the environment and resource categories above. The social mega-category was composed of the social impacts, values, temporal, spatial unbalances, education, and actors/stakeholders categories above. The economic mega-category was composed of the economic and technology categories above.

Table 3.10. Metrics to score cmaps using categorical method (Adapted from Segalàs et al. [152]).

	For an individual student *j*:	For a cohort of students:
Category Analysis	$CD_{i,j} = \frac{NC_{i,j}}{\sum_{i=1}^{N_{Cat}} NC_{i,j}}$	$CR_i = \frac{CD_i \left(NS_i / NS \right)}{\sum_{i=1}^{N_{Cat}} \left[CD_i \left(NS_i / NS \right) \right]}$
Complexity Analysis	$\left(L_{Cat}\right)_j = \frac{NIL_j}{N_{Ca}}$ $CO_j = NC_j * \left(L_{Ca}\right)_j$	$\left(L_{Cat}\right)_{avg} = \frac{\sum_{j=1}^{NS} NIL_j}{N_{Ca} * NS}$ $CO_{cohort} = NC_{avg} * \left(L_{cat}\right)_{avg}$
Variable Descriptions	Where, $CD_{i,j}$ = concept distribution displayed for category *i*; $NC_{i,j}$ = number of concepts included in category *i*; $(L_{cat})_j$ = Relative number of inter-links; NIL_j = number of interlinks between concepts from different categories; CO_j = student-specific complexity index; CR_i = category *i* relevance; NS_i = number of students including concepts from category *i*; NS = total number of students in cohort; $(L_{cat})_{avg}$ = average relative number of interlinks for cohort; CO_{cohort} = cohort-specific complexity index; NC_{avg} = average number of concepts for cohort.	

Judge Training and Scoring Calibration

Judges were trained to use traditional, holistic, and categorical scoring methods before rating student cmaps. Three cmaps constructed by capstone students were selected and judges individually quantified parameters for each of the three scoring approaches. Scores provided by the two judges for all methods were similar; however, any differences were discussed and resolved to promote consensus among future scores. Afterward, three additional capstone cmaps were individually scored and discussed by judges. Krippendorff's alpha for the final training session were at least 0.67 for each method, which is appropriate for exploratory research [186].

Several consensus guidelines for scoring cmaps emerged from the judge training sessions. While the traditional scoring method was designed to be objective, quantification of highest level of hierarchy and number of cross-links proved to be difficult for complex cmaps. As a result, judges devised and followed a systematic procedure that involved assigning concepts to a hierarchy, identifying cross-links, and counting the level of a hierarchy as the number of concepts in that hierarchy until a cross-link was reached (Figure 3.7). Clarifications were also made to the comprehensiveness and organization components of the holistic rubric (Table 3.8), including defining complete "subject definition" [131] as inclusion of four major sustainability dimensions [152]: economic, environment/natural resources, social, and temporal. For the categorical method, examples of concepts belonging to each of the 10 sustainability categories provided by Coral [197] were supplemented with examples from practice cmaps to guide concept categorization (Table 3.9). Thus, the training sessions allowed judges to discuss the details of each scoring method and calibrate scoring criteria to promote interrater reliability.

Consensus Scoring of Concept Maps

Remaining cmaps not used for training purposes were evaluated by judges. Cmaps were coded and provided to judges in random order to minimize scoring bias. Using the traditional (Table 3.7), holistic (Table 3.8), and categorical (Table 3.9) methods, judges individually quantified scoring parameters. Differences in scores were discussed by the judges and consensus scores were used in all subsequent statistical analyses.

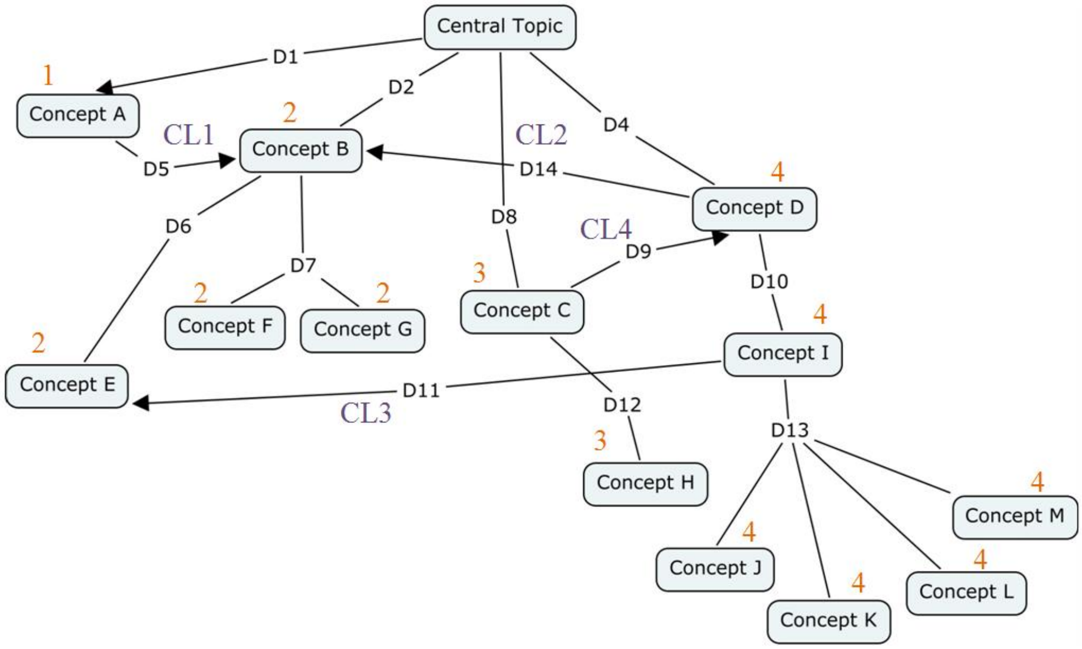

Figure 3.7. Application of traditional scoring method using conventions devised by judges. Scores assigned as follows: NC = 13; HH = 3; NCL = 4. By convention, linking lines read from top to bottom to not include arrow heads.

<u>Statistical Analysis of Concept Map Scores</u>

Interrater Reliability

Interrater reliability for each concept map scoring approach was quantified by computing Krippendorff's alpha using judges' individual scores (Table 3.11). The traditional and most objective method yielded the highest statistics, with Krippendorff's alpha within the adequately acceptable range ($\alpha \geq 0.80$) [186]. The categorical method, which requires somewhat subjective assignment of concepts according to a ten-category taxonomy [118], also exhibited Krippendorff's alpha within the adequately acceptable range ($\alpha \geq 0.80$) [186]. The holistic approach, which relies on judges to apply a rubric in scoring cmaps, showed the lowest interrater reliability statistics, although Krippendorff's alpha were within the acceptable for exploratory research ranges ($\alpha \geq 0.67$) [186]. Thus, the traditional, holistic, and categorical scores presented for student sustainability cmaps in the current work are reliable.

Table 3.11. Interrater reliability of cmap scoring methods (n = 484, unless otherwise noted).

	Krippendorff's Alpha
Traditional Method	
Number of concepts	0.999
Highest hierarchy	0.958
Number of cross-links	0.977
Holistic Method	
Comprehensiveness	0.860
Organization	0.777
Correctness	0.803
Categorical Method	
Classification of concepts	0.844[a]
Number of inter-links	0.990

[a]Number of concepts = 9166.

Convergent Validity

Since the traditional and holistic methods are intended to characterize similar cmap qualities, correlations between sub-scores were analyzed to establish convergent validity (Table 3.12). To assess knowledge breadth (content) and depth (structure), the traditional method uses number of concepts and highest hierarchy, respectively, while the holistic approach considers the composite parameter of comprehensiveness. Accordingly, highest Spearman correlations were demonstrated between comprehensiveness and both number of concepts (ρ = 0.676) and highest hierarchy (ρ = 0.404). The holistic organization sub-score is an indicator of cmap connectedness and appropriate hierarchical placement of concepts. As a result, high Spearman correlations were found between organization and both highest hierarchy (ρ = 0.329) and number of cross-links (ρ = 0.532). Appropriate correlations between traditional and holistic sub-scores that quantify similar cmap characteristics and lack of high correlations between sub-scores that quantify different cmap qualities suggest convergent validity for the two scoring approaches. Thus, both traditional and holistic scoring methods proved to be valid for evaluating the breadth, depth, and connectedness of sustainability knowledge depicted in cmaps.

Convergent validity of overall cmap metrics was also investigated (Table 3.13). Each the total traditional score, total holistic score, and category index (CO_j) are metrics that describe the overall quality of a cmap. Accordingly, significant relationships were found between CO_j and the total traditional (ρ = 0.745) and total holistic scores (ρ = 0.660).

Table 3.12. Correlations between traditional and holistic cmap sub-scores (*n* = 490).

	Number of Concepts	Highest Hierarchy	Number of Cross-Links
Comprehensiveness	0.676***	0.401***	0.163***
Organization	0.177***	0.327***	0.589***
Correctness	0.180***	0.150***	0.044

***$p \leq 0.001$

Table 3.13. Correlations between overall cmap scores (n = 490).

	CO_j
Total Traditional Score	0.745***
Total Holistic Score	0.660***

***$p \leq 0.001$

Inferential Statistics

After computation of interrater reliability and convergent validity statistics, consensus scores were used for all further statistical analyses. ANOVA tests were used to capture differences between cmap scores (interval or ratio data) based on independent (categorical) variables, such as gender, country of origin, and/or academic cohort. Significant differences were identified as those yielding p-values less than or equal to 0.05.

Sustainable Design Rubric for Applied Sustainability Knowledge Assessment

The Sustainable Design Rubric was developed and applied to quantify students' abilities to apply sustainability principles during the capstone design process. While conceptual understanding of sustainability is paramount, it is critical that engineers be able to apply this knowledge during design. Sustainable design assessments included (1) development of the Sustainable Design Rubric, (2) evaluating capstone projects using the rubric, and (3) analyzing rubric scores using statistical analyses (Figure 3.8).

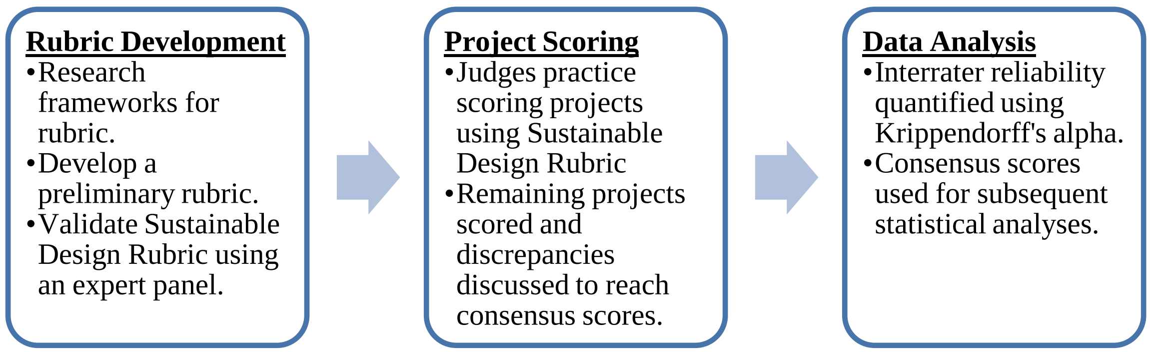

Figure 3.8. Process for developing and applying the Sustainable Design Rubric.

<u>Rubric Development</u>

A sustainable design rubric was developed to characterize students' sustainable design abilities. In designing the rubric, one goal was to produce a tool that could be easily applied to a variety of CEE-related student projects. Because of the structure of the CEE capstone design at Georgia Tech (see "Case Study Context" above), the rubric needed to capture not only the extent to which students engage in sustainable design, but also the influence of project sponsors and/or course instructors on sustainable design expectations. Development of this tool was completed using a three-phase process.

Phase 1: Researching Existing Sustainability Evaluation Frameworks

In Phase 1, existing frameworks potentially applicable for evaluating sustainability content of student design projects were investigated (see *Chapter Two* for more details). LEED, which provides a comprehensive rating system for quantifying the sustainability of buildings [164], was deemed inappropriate because it would not allow for evaluation of a wide range of CEE student projects, such as those related to transportation or environmental engineering. While Envision^{TM}, endorsed by ASCE, was developed to be applicable for a variety of infrastructure projects [198], it requires scoring of 60 criteria, which would be tedious to apply to student projects. Even if time were available to complete the evaluation, many of the criteria are too detailed to be addressed in a semester- or year-long project. For instance, to meet the “assess climate threat” criterion (CR2.1), students would have to complete a Climate Impact Assessment and Adaptation Plan. Similarly, to meet the “reduce net embodied energy” criteria (RA1.1), students would have to complete a life-cycle energy assessment. Overall, existing project-level assessment frameworks were concluded to be too narrow in scope and/or require unreasonably detailed design analysis for student capstone projects.

Although no existing frameworks were found to be applicable to student projects, the Nine Principles of Sustainable Engineering were identified as having potential for serving as the foundation for developing a set of sustainable design criteria (Table 2.10). Not only are the Nine Principles applicable to a range of CEE capstone projects, they are also relevant for other engineering disciplines. Second, basing project evaluation criteria on expert-derived sustainability principles is advantageous because it helps promote content validity of the evaluation tool. Thus, the Nine Principles were identified as a more suitable framework for evaluating student design projects than existing evaluation tools for large-scale projects.

Phase 2: Developing a Preliminary Project Evaluation Rubric

1. Specifying Sustainable Design Criteria

During Phase 2, a preliminary sustainable design rubric was developed based on the Nine Principles of Sustainable Engineering and the four basic components of an analytical rubric, as suggested by Allen & Tanner [162]. Since many of the Nine Principles are complex and incorporate multiple ideas, each principle was decomposed into discrete design criteria to aid in ease of rubric application. For instance, the second principle (Table 2.10) was separated into two sustainable design criteria: (1) conserve natural ecosystems and (2) protect human health and well-being. Deconstruction of the Nine Principles yielded 13 sustainable design criteria. Since the economic dimension of sustainability is not explicitly represented by the Nine Principles, the set of 13 criteria was supplemented with three economic design criteria. As a result, a system of 16 sustainable design criteria by which to judge the sustainability content of student capstone projects was established (Table 3.14).

2. Supplementing Sustainable Design Rubric with Examples

To aid judges in identifying application of criteria in project reports, a set of examples for how the 16 criteria may be met in CEE projects was compiled (Table 3.15) (See Appendix B for comprehensive list). This phase was essential for elucidating what each criterion "looks like" in student projects, as suggested by Allen & Tanner [162]. First, capstone design reports completed by CEE students in Fall 2010 were evaluated using the rubric, and instances of criteria consideration were recorded. Afterward, Fall 2007 projects were examined using the amended rubric and any new examples were recorded. This process was repeated for Fall 2004 and Fall 2001 projects. As a result, a comprehensive list summarizing how CEE students may incorporate sustainable design criteria into capstone projects was developed to supplement the rubric.

3. Creating Rating Scales

Two four-point rating scales were created to aid evaluators in judging capstone reports based on the 16 sustainable design criteria (Table 3.16). The earned points scale was specified to capture the extent to which students considered each sustainable design criteria in their capstone project. A score of "0" corresponds to a project that shows no evidence of incorporating the design criterion, while a score of "3" is assigned if the project shows evidence of extensive criterion application. Application of the earned points scale for some criteria requires additional specifications (Table 3.17), including many of those comprising the Sustainable Design Tools category. The potential points scale describes the extent to which each sustainable design criteria is applicable to a given capstone project. A score of “0” is awarded if the criterion is not applicable to the project, while a score of “3” is assigned if the criterion is not only applicable, but consideration was dictated by an instructor or project sponsor. Rating projects on both the extent of consideration and level of applicability allows for differentiation between sustainability application due to student motivation and sponsor requests.

4. Formulating Sustainable Design Metrics

Several metrics were designated to evaluate and compare rubric scores (Table 3.18). Raw scores for each criterion (*i*), including earned (E_i) and potential (P_i) points, were used to provide insights into the extent of criterion consideration and level of criterion applicability, respectively. Using raw scores, means for each rubric category (environmental, social, sustainable design tools, and economic) were also computed. The final sustainable design index was quantified as the difference between mean potential (M_{pot}) and mean earned (M_{earn}) scores. As a result, a sustainable design index of +3 represents a project with high sustainable design expectations and low student performance. Conversely, an index of -3 is characteristic of a project with low sustainable design requirements and high student performance. A sustainable design index near zero represents a project that largely met sustainable design expectations (Figure 3.9).

Phase 3: Validation of Sustainable Design Rubric

Content validity of the rubric was established through assessment by an expert panel, which has been endorsed by other researchers [199-201]. Graduate student panelists included three graduate students from civil, environmental, and aerospace engineering, each conducting research broadly associated with sustainability. Faculty panelists consisted of two CEE faculty members who had experience facilitating capstone design, as well as an educational psychologist. Each panelist reviewed the Sustainable

Design Rubric, and then responded to several questions related to the appropriateness of the rubric for capstone projects:

1. Are the 9 Sustainable Design Principles, developed by experts at the 2002 Green Engineering Conference, an appropriate framework for a sustainable design rubric (Table 2.10)?
2. Are the 16 sustainable design criteria appropriate for evaluating student projects (Table 3.14)?
3. Are the earned points and potential points rating scales comprehendible (Table 3.16)?
4. Are the special considerations for application of potential points rating scale reasonable (Table 3.17)?
5. Are examples of sustainable design criteria consideration properly classified (Table 3.15)?
6. Are sub-scores and total scores appropriate for comparing sustainability content of capstone projects (Table 3.18)?

Panelists were also encouraged to provide open-ended feedback. Suggestions, especially related to classification of sustainable design examples, were incorporated into the final rubric.

Table 3.14. Sample scoring rubric, including the 16 sustainable design criteria, used to evaluate capstone design projects.

Design Criteria	Potential Points[a]	Earned Points[a]
Environmental Design Criteria		
1. Minimizes natural resource depletion	1-3	0-3
2. Prevents waste	1-3	0-3
3. Protects natural ecosystems	1-3	0-3
4. Uses renewable energy sources	1-3	0-3
5. Uses inherently safe and benign materials (to environment)	1-3	0-3
Social Design Criteria		
6. Addresses community and stakeholder requests	1-3	0-3
7. Considers local circumstances and cultures	1-3	0-3
8. Protects human health and well-being	3	0-3
9. Uses inherently safe and benign materials (to humans)	1-3	0-3
Sustainable Design Tools		
10. Incorporates life cycle analysis	1-3	0-3
11. Incorporates environmental impact assessment tools	1-3	0-3
12. Incorporates systems analysis	1-3	0-3
13. Uses innovative technologies to achieve sustainability	1-3	0-3
Economic Design Criteria		
14. Consider economic impacts of applying environmental design criteria.	1-3	0-3
15. Consider economic impacts of applying social design criteria.	1-3	0-3
16. Conduct a cost and/or cost-benefit analysis	2	0-3

[a]See Table 3.16 for potential and earned points rating scales, which both range from 0 to 3. Values shown above summarize scoring conventions used for the current investigation.

Table 3.15. Example applications of sustainable design criteria in capstone design projects.

Environmental Design Criteria	Examples
Minimizes natural resource depletion	• Promoting use of non-fossil-fuel-based transportation (e.g. providing bike racks, reducing number of parking spaces, or other techniques that do not include using renewable energy sources). • Decreasing fossil fuel consumption by using local materials.
Prevents waste	• Minimizing material waste during construction. • Providing opportunities for users of a project to recycle.
Protects natural ecosystems	• Preventing release of pollutants into water sources. • Using vegetation to preserve water quality (e.g. use of green spaces, stream buffers, landscaping islands).
Uses inherently safe and benign materials (to environment)[1]	• Use of materials whose production as low environmental impacts (e.g. construction concrete and steel). • Use of certified environmentally-safe materials.
Uses renewable energy sources	• Incorporation of on-site renewable energy (wind, hydropower, solar, bio-based, geothermal) into design. • Providing preferred parking for alternative fuel vehicles.
Social Design Criteria	**Examples**
Addresses community and stakeholder requests	• Improvements to traffic congestion (e.g. minimizing queuing at traffic signals, improving level of service). • Avoiding routing traffic through residential areas.
Considers local circumstances and cultures	• Designing projects to blend in with the aesthetic qualities of the community. • Honoring historical sites that must be altered during design (e.g. adding commemorative plaques).
Protects human health and well-being	• Addressing driver expectancy issues (e.g. with appropriate signs) • Adding appropriate measures to prevent flooding (e.g. detention ponds, drainage improvements).
Uses inherently safe materials (to humans)[1]	• Use of low or non-toxic materials (e.g. non-carcinogens, non-irritants) • Use of materials that require non-toxic cleaning procedures.

Sustainable Design Tools	Examples
Incorporates life cycle analysis	• Considering impacts of project over its lifecycle, rather than just its useful life. • Using results from a life cycle analysis.
Incorporates environmental impact assessment tools	• Recommending that an environmental impact assessment be completed or completing preliminary steps of an assessment. • Using results from an environmental impact assessment.
Incorporates systems analysis	• Defining the project system by setting boundaries, defining system components and attributes, and explaining links between system components and attributes. • Determining project impacts (economic, environmental, social) within and outside of system boundaries.
Uses innovative technologies to achieve sustainability	• Designing for LEED certification. • Using non-typical solutions for a geographical area (e.g. roundabouts uncommon in GA).
Economic Design Criteria	Examples
Considers economic impacts of meeting environmental design criteria	• Finding cost-effective methods or strategies for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit while enacting an environmental sustainability principle (e.g. charge extra for residential units located near green space).
Considers economic impacts of meeting social design criteria	• Finding cost-effective methods for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit from enacting a social sustainability principle (e.g. adding commercial space near residential areas to increase property values).
Conducts a cost and/or cost-benefit analysis	• Estimation of project costs. • Use of cost-benefit analyses.

Table 3.16. Rating scales for awarding earned and potential points.

Earned Score	Descriptor	Dimension Description
0	Unacceptable	Criterion not at all considered in project report.
1	Developing	Criterion mentioned or discussed in the project report, but not applied in design process.
2	Competent	Project report shows evidence that the criterion was adequately applied in design process (1-2 instances of criterion application).
3	Exemplary	Project report shows evidence that the criterion was extensively applied in the design process (3 or more instances of criterion application).
Potential Score	**Descriptor**	**Dimension Description**
0	Inapplicable	The criterion is not at all valid for the project.
1	Valid	Although the sponsor does not require application of the criterion, it is still applicable to the project.
2	Required	The sponsor requires some application of the criterion in the project (1-2 instances of requiring criterion application).
3	Critical	The sponsor requires extensive application of the criterion in the project (3 or more instances of requiring criterion application).

Table 3.17. Interpretation of earned points rating scale for selected criteria.

Criterion	Score = 1	Score = 2	Score = 3
Incorporates life cycle analysis (LCA)	• Mentions need for LCA and/or considers 1 stage beyond immediate use.	• Considers 2-3 stages beyond immediate project use.	• Considers more than 3 stages beyond immediate project use.
Incorporates environmental impact assessment (EIA) tools	• Mentions the need for EIA and/or begins to formulate EIA through description of potential impacts.	• Develops abbreviated EIA through estimation of environmental impacts of multiple design alternatives.	• Completes full EIA OR fulfills score 2 requirements and recognizes need for extended EIA.
Incorporates systems analysis	• Understands project is part of a larger system. Demonstrated by defining boundaries or project context.	• Considers 1-2 linkages (economic, environmental, or social) that connect project to larger system.	• Considers more than 3 linkages (economic, environmental, or social) that connect project to larger system.
Economic analysis	• Completes a cost estimate for only one design alternative.	• Completes a cost estimate for more than one design alternative.	• Meets score 2 criteria and incorporates cost/benefit analysis.

Table 3.18. Sustainable design metrics for use with the Sustainable Design Rubric.

	Range	Potential Scale	Earned Scale
Environmental Design Mean	[0, 3]	$M_{\text{env,pot}} = \sum_{i=1}^{5} P_i \Big/ 5$	$M_{\text{env,pot}} = \sum_{i=1}^{5} E_i \Big/ 5$
Social Design Mean	[0, 3]	$M_{\text{soc,pot}} = \sum_{i=6}^{9} P_i \Big/ 4$	$M_{\text{soc,pot}} = \sum_{i=6}^{9} E_i \Big/ 4$
Sustainable Design Tools Mean	[0, 3]	$M_{\text{tools,pot}} = \sum_{i=10}^{13} P_i \Big/ 4$	$M_{\text{tools,pot}} = \sum_{i=10}^{13} E_i \Big/ 4$
Economic Design Mean	[0, 3]	$M_{\text{tools,pot}} = \sum_{i=14}^{16} P_i \Big/ 3$	$M_{\text{tools,pot}} = \sum_{i=14}^{16} E_i \Big/ 3$
Potential or Earned Score Mean	[0, 3]	$M_{\text{pot}} = \sum_{i=1}^{16} P_i \Big/ 16$	$M_{\text{earn}} = \sum_{i=1}^{16} E_i \Big/ 16$
Sustainable Design Indicator	[-3, 3]	$SD_{\text{score}} = M_{\text{pot}} - M_{\text{earn}}$	

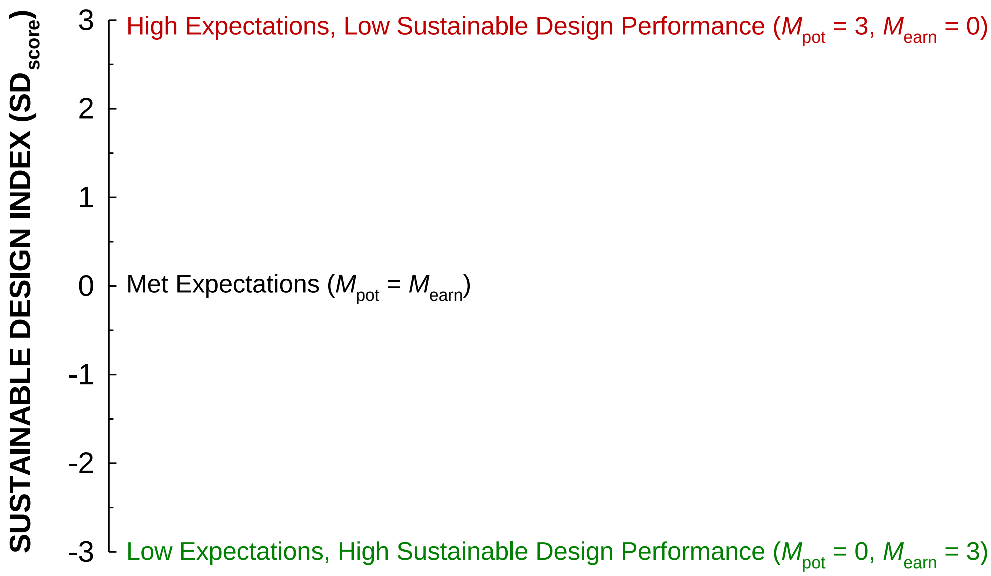

Figure 3.9. Scale for Sustainable Design Index (SD_{score}).

Project Scoring

Expert Judges

Three graduate students served as judges to evaluate capstone projects. The lead judge was the developer of the rubric, as well as a PhD candidate in environmental engineering. Both additional judges were PhD candidates in civil engineering at the time the research was completed. All judges were designated as "experts" due to extensive knowledge of sustainability gained through completion of relevant coursework and/or research.

Judge Training and Scoring Calibration

To ensure competency and consistency in scoring, all three judges participated in a training session to encourage interrater reliability, as suggested by Bresciani et al. [202]. Judges were first familiarized with the sustainable design criteria and related rating scales (Tables 3.14-3.18). Some rating conventions were specified during the training periods. For "protects human health and well-being" judges were to give a default potential rating of "3," due to ethical requirements for all CEE projects specified by ASCE [40]. Similarly, judges awarded a standard potential score of "2" for "conducts a cost and/or cost-benefit analysis," since student groups were required to complete economic analysis as part of the course requirement. In the event that no evidence was found to suggest that the group was required to meet a criterion and no special scoring consideration applied (Table 3.17), judges were directed to give potential scores of "1" for all criteria, since they are broadly applicable to all CEE projects.

To calibrate scoring, judges examined several projects that were not being used as part of the research study. First, the group discussed application of the potential and earned points scale using a project that was pre-scored by the lead judge. Afterward, each judge practiced applying the rubric to three capstone design projects. The lead judge met individually with other judges to discuss discrepancies and reach a set of consensus scores.

Consensus Scoring of Capstone Projects

After judges were trained, the group used the rubric to score a sample of capstone design projects (Fall 2002, Fall 2006, Fall 2011, and Spring 2012). The lead judge evaluated each project, while additional judges each examined half of the project set. As a result, each project was reviewed by two different judges. Individual scores were recorded and any discrepancies were discussed to reach a set of consensus scores, as per Besterfield-Sacre et al. [131]. Thus, for each project, data included judges' individual potential and earned ratings for each criterion, as well as consensus potential and earned points scores for each criterion.

Statistical Analysis of Project Scores

Interrater Reliability

Interrater reliability, quantified using Krippendorff's alpha, was acceptable for sustainable design scores. In fact, interrater reliability statistics for potential and earned scores for all criteria were 0.784 and 0.782, respectively. These values are within Krippendorff's range deemed "acceptable for exploratory research" [186].

Inferential Statistics

Judge's consensus scores were used for all subsequent statistical analyses. To provide insight into areas of student design proficiency and deficiency, SPSS was employed to conduct paired-samples *t*-tests to compare mean potential and earned scores for each of the 16 sustainable design criteria. Differences in scores (ratio data) over time (ratio data) were detected using regression analysis, while changes due to project type (nominal data) were analyzed using ANOVA. Significant differences were identified as those yielding *p*-values less than or equal to 0.05.

Surveys for Assessment of Student Perceptions

Several surveys were developed and administered to undergraduate CEE students to gain insights into their perspectives on sustainability and sustainability education (Table 3.19). Specifically, the Student Sustainability Survey was used to examine interest in, knowledge of, and experiences related to sustainability, while the Student Curriculum Survey was used to collect student opinions related to the CEE curriculum. Finally, the Module Evaluation Survey was used to elicit comments and suggestions for improving implementation of a learning-cycle-based sustainability module into capstone and cornerstone design courses. All survey studies were conducted in three phases: (1) survey development, (2) survey administration, and (3) data analysis (Figure 3.10).

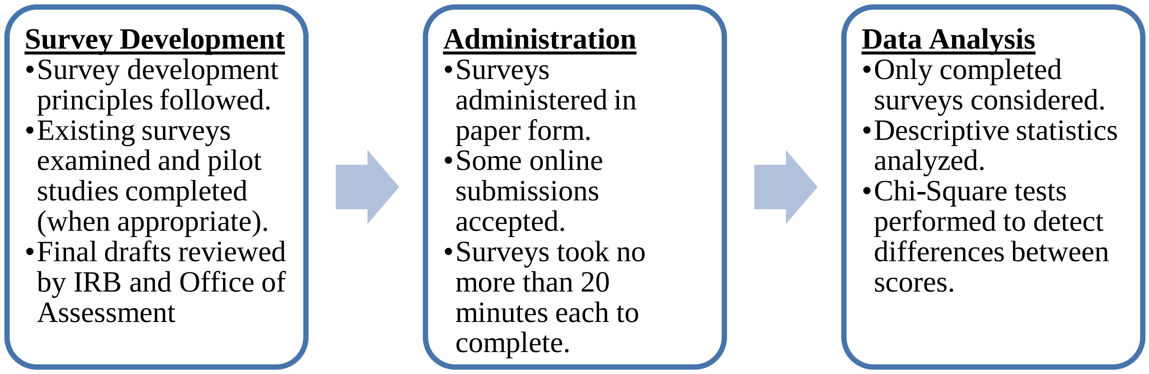

Figure 3.10. Method for conducting survey studies (informed by [203, 204]).

Table 3.19. Summary of surveys used to explore student insights into sustainability and sustainability education (See Appendices C-F).

Survey	Details
Student Sustainability Survey	• Rate importance of/confidence in the ability to demonstrate conceptual understanding of sustainability. • Rate importance of/confidence in the ability to apply sustainability principles during design. • Rate interest in sustainable development and many related topics. • Rate overall quality of CEE sustainability education. • Rate importance of implementing several strategies for improving CEE sustainability education. • Rate influence of sustainability interest on academic and career goals.
Student Curriculum Survey	• List up to five CEE courses that addressed sustainability. • Rate extent to which economic, environmental, social, and cross-cutting STAUNCH® topics were addressed in their CEE courses.
Module Evaluation Survey	• Provide open-ended feedback on several separate occasions throughout module implementation. • Rate overall satisfaction with module.

Development of Surveys

Student Sustainability Survey

The Student Sustainability Survey was developed to gain insights into student perspectives of sustainability and sustainability education. First, existing surveys in the literature were consulted to develop relevant questions [119, 134, 205-207]. Next, a preliminary survey was developed using expert-derived survey design principles [208-210] to ensure proper clarity and objectivity of items. Afterward, the survey was reviewed by the Georgia Tech Office of Assessment and Institutional Review Board (IRB) to ensure quality and compliance with all human subjects protocols, as was suggested by other authors [203, 204]. To establish content validity, feedback was elicited from a panel of three CEE graduate students and appropriate modifications were made. Finally, the survey was piloted to 19 undergraduate students enrolled in an undergraduate CEE course, and minor suggestions were incorporated.

The final survey prompted students to reflect on sustainability education using seven-point scales. Students rated both the importance for engineers to be able to, as well as their confidences in their own abilities to, demonstrate conceptual and applied understanding of sustainability. In addition, students were asked to indicate their interest in sustainability topics and describe how their interest may or may not have affected important professional choices. Finally, students rated the contribution of several curricular and extra-curricular activities to their own sustainability learning (See Appendix C for a copy of the survey).

Student Curriculum Survey

The Student Curriculum Survey (Appendix D) was developed to gain insight into how extensively students viewed sustainability as being integrated into the CEE curriculum. The survey, developed using expert-derived survey design principles [208-210], prompted students to use a seven-point scale to rank the extent of coverage of each of the 40 STAUNCH® key topics (Table 3.4) by their CEE courses. In addition, students were prompted to list up to five CEE courses that extensively addressed sustainability. The survey was reviewed by the Georgia Tech Office of Assessment and IRB to ensure proper format and readability, as suggested by other authors [203, 204].

Module Evaluation Survey

The Module Evaluation Survey was developed to inquire about student satisfaction with a sustainability module, which was implemented into capstone (Appendix E) and cornerstone (Appendix F) courses. Open-ended suggestions for improving the module were elicited throughout implementation. In addition, after module completion, students were asked to use a seven-point scale to rate the extent to which they agreed or disagreed with the following statements: (1) participating in the sustainability module helped me learn about sustainability concepts, (2) participating in the sustainability module helped me learn about sustainable design, and (3) I enjoyed participating in the module. The survey was reviewed by the Georgia Tech Office of Assessment and IRB, as suggested by other authors [203, 204].

Administration of Surveys

Surveys were administered to students in paper-form during designated class time. If students were absent from class, they were permitted to complete an identical online version. Students were provided with unlimited time to complete surveys, although most students only required 15-20 minutes per survey.

Analysis of Surveys

Chi-Square tests were used to evaluate all survey results. For each survey item, the proportion of students indicating a response of six or seven on a seven-point scale ($\pi_{6\text{-}7}$) was compared to the proportion of students providing a response less than six. Significant differences were identified as those yielding *p*-values of 0.05 or less.

Methods for Assessing the Quality of Sustainability Education in CEE at Georgia Tech (Goal 1)

With several organizations calling for higher education to train engineers to engage in sustainable design [1, 18, 23], the initial phase of this research involved investigating the efficacy of sustainability education in CEE at Georgia Tech. Given that the curriculum has the potential to significantly impact student learning, the sustainability content of CEE courses was first examined.   In addition, the sustainability knowledge of seniors was quantified to characterize the level of sustainability knowledge possessed by soon-to-be CEE graduates. Overall, this research phase was designed and implemented to benchmark the current status and outcomes of CEE education to identify strategies for enhancing student learning about sustainability.

Question 1.1: What do students' perspectives reveal about their sustainability education?

As the primary beneficiaries of sustainable education, CEE student perspectives must be considered in any reform effort. Seniors in particular have unique perspectives because they have just recently completed a majority of their educational programs. The Student Sustainability Survey (Table 3.19) was administered to seniors enrolled in the Fall 2011 and Spring 2012 capstone design courses to collect data regarding their interest in, knowledge of, and previous experiences related to sustainability education, as per the surveying methodology (Figure 3.10). Survey results were used to examine the role that the CEE curriculum plays in sustainability education, as well as gauge student reactions to instituting program reforms. Student perceptions of their own sustainability knowledge (both conceptual and applied) were collected for later compassion to more objective knowledge assessments (concept map assessments and capstone project evaluations).   Analysis of survey results included computation of descriptive statistics, as well as use of Chi-Square tests to detect differences between various demographic groups (e.g. civil engineers versus environmental engineers; males versus females; domestic versus international students). Ultimately, understanding the student perspective can help in designing well-received educational interventions that address students' academic needs.

Question 1.2: To what extent is sustainability currently integrated into the CEE curriculum?

Given the potential impact of CEE courses on student sustainability learning, the sustainability content of the curriculum was examined using the STAUNCH® framework. An independent audit of CEE courses was conducted using STAUNCH®, although validity of results requires that courses are disseminated as outlined in their syllabi. To supplement this analysis, student experiences in the CEE courses themselves were gathered through surveys. Evaluating the curriculum using both published course materials and student perspectives was intended to provide a holistic assessment of sustainability content (Figure 3.11).

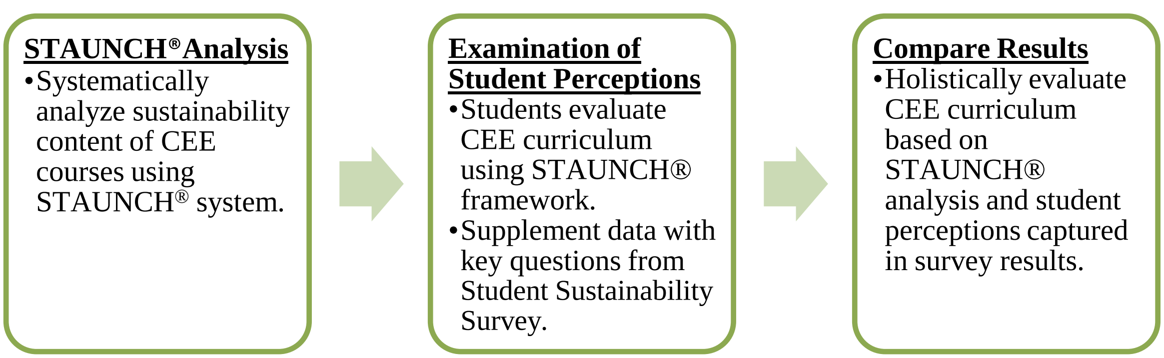

Figure 3.11. Method for evaluating sustainability content of the CEE curriculum.

Formal STAUNCH® Assessment of the CEE Curriculum

The STAUNCH® system was used to systematically examine the sustainability content of CEE courses offered during the 2010-2011 academic year. As per the STAUNCH® method (Figure 3.4), syllabi for CEE courses were obtained from the confidential 2008 ABET Self-Study Report prepared by the School [181]. Syllabi presented in this report follow a uniform format that include the catalog description, supporting textbooks, learning outcomes, topics covered, and contribution to ABET program objectives. It was assumed that the 2008 syllabi have remained relatively unchanged and are thus valid for analysis of the 2010-2011 academic year. For new courses not included in the 2008 report, syllabi were obtained from course instructors. If syllabi were not available from course instructors, then the description published in the 2010-2011 Georgia Tech Course Catalog was used [182]. Enrollment numbers for each course were obtained from the Georgia Tech CEE Student Services Office [211]. In total, syllabi for 44 courses were obtained for STAUNCH® analysis (Table 3.20). Next, in coordination with Dr. Rodrigo Lozano from Organisational Sustainability, each course descriptor was examined for evidence of coverage of each for the 40 STAUNCH® topics (Table 3.4). Evidence was scored using a four-point scale (Table 3.5) and resulting data was inputted into STAUNCH® for analysis. Organizational Sustainability provided a detailed report of the STAUNCH® analysis (Appendix G), including strength and contribution metrics [124].

Student Curricular Assessment using the STAUNCH® Framework

Student perceptions of the CEE curriculum and overall sustainability education were investigated using the Student Curriculum Survey and some items from the Student Sustainability Survey (Table 3.19). As per the surveying methods (Figure 3.10), students enrolled in the Spring 2012 CEE capstone design course were directed to indicate the extent of coverage of each of the 40 STAUNCH® topics using a seven-point scale through completion of the Student Curriculum Survey. Items from the Student Sustainability Survey, including questions to rate the overall quality and need to improve of CEE sustainability education, were used to supplement data from the Student Curriculum Survey. Ultimately, student perceptions were compared with STAUNCH® results to holistically evaluate the current status of the CEE curriculum.

Table 3.20. Summary of 2010-2011 CEE courses analyzed using STAUNCH®.

Course Number	Course Title	Credits	No. Students
CEE 1770	Intro to Engr Graphics	3	267
CEE 2040	Dynamics	2	221
CEE 2300	Environmental Engr Prin	3	313
CEE 3000	Civil Engr Systems	3	324
CEE 3010	Geomatics	3	126
CEE 3020	Civil Engr Material	3	207
CEE 3040	Fluid Mechanics	3	249
CEE 3055	Structural Analysis	3	225
CEE 3340	Environ Engr Laboratory	3	25
CEE 3770	Statistics & Applications	3	153
CEE 4090	Capstone Design	3	225
CEE 4100	Construction Engr & Mgt	3	272
CEE 4101	Construction Seminar	1	126
CEE 4120	Construction Operations	3	63
CEE 4200	Hydraulic Engineering	3	115
CEE 4210	Hydrology	3	87
CEE 4225	Coastal Engineering	3	31
CEE 4300	Environmental Engr Sys	3	117
CEE 4310	Water Quality	3	45
CEE 4320	Hazardous Substance Engr	3	35
CEE 4330	Air Pollution Engr	3	29
CEE 4395	Environmental System Design	3	21
CEE 4405	Geotechnical Engr	3	175
CEE 4510	Structural Steel Design	3	164
CEE 4520	Reinforced Concrete Design	3	133
CEE 4530	Timber & Masonry Design	3	56

CEE 4540	Infrastructure Rehab	3	52
CEE 4550	Structural Analysis II	3	77
CEE 4600	Transportation Plan & Design	3	163
CEE 4620	Environ Impact Assess	3	49
CEE 4640	Freeway & Interchange Design	3	40
CEE 4650	Site Design in Transport	3	19
CEE 4791	Mechanical Behavior of Composites	3	6
CEE 4793	Composite Material & Process	3	2
CEE 4801B	Special Topics: Marine Renewable Energy	1	5
CEE 4801 RPK	Special Topics: GTS 2000	1	43
CEE 4802A	Special Topics: VIP eStadium	2	2
CEE 4803B	Special Topics: Sustainable Engineering	3	18
CEE 4801RK2[a]	Special Topics: Engineering Alliance Seminar	1	39
CEE 4801RPK[a]	Special Topics: Engineering as a Profession	1	55
CEE 4803A[a]	Special Topics: Transit Sys Plan & Design	3	43
CEE 4803B[a]	Special Topics: Construction Safety & Health	3	35
CEE 4803C	Special Topics: Applied Geotechnique	3	19
CEE 4803D[a]	Special Topics: Project Planning & Monitoring	3	28

[a]Syllabi not available from course instructor. Course description used as descriptor.

Question 1.3: How Advanced is Students' Conceptual Understanding of Sustainability?

In addition to examining the curriculum itself, the conceptual knowledge of students having largely completed their CEE courses was also examined. While student surveys are the primary method discussed in the literature for assessing student sustainability knowledge [132-135], student perceptions of their cognitive abilities are known to be fallible [212-214]. As a result, in addition to student surveys, concept-map-based assessments were used as a more objective measure of student understanding.

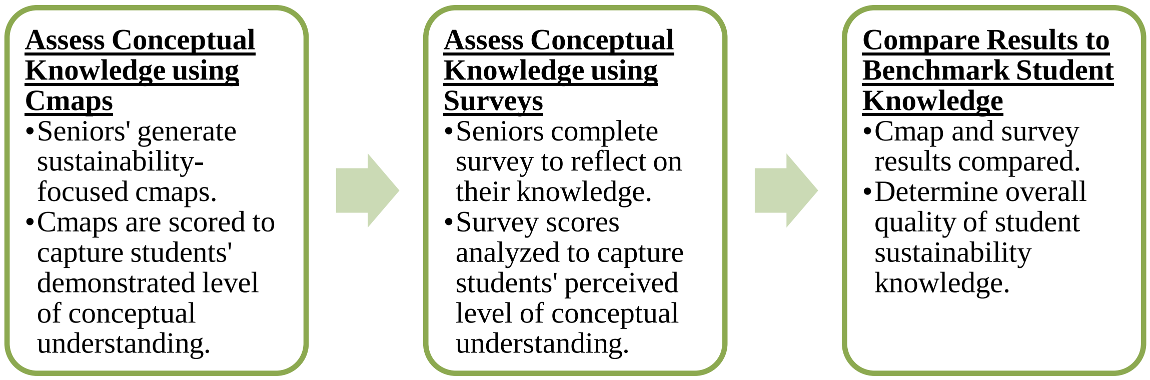

Figure 3.12. Method for evaluating student sustainability knowledge of seniors having nearly completed the CEE curriculum.

<u>Concept-Map-Based Knowledge Assessments</u>

Students enrolled in capstone design courses (Fall 2011 and Spring 2012) were prompted to showcase their sustainability knowledge by constructing cmaps. According to the concept mapping methods (Figure 3.6), students generated sustainability-focused cmaps within the first two weeks of the semester. Expert judges used three different scoring methods to extract quantitative data from the student cmaps to characterize both the content and structure of student sustainability knowledge.

<u>Student Perceptions of their Conceptual Knowledge</u>

Several items from the Student Sustainability Survey were used to capture students' perceptions of their conceptual sustainability knowledge. Following the surveying methods (Figure 3.10), students were asked to rate their abilities to discuss the overall topic of sustainability, as well as the more specific economic, environmental, and social sustainability dimensions. Cmap scores and survey responses were ultimately compared to provide a complete analysis of the quality of students' conceptual sustainability knowledge (Figure 3.12).

Question 1.4: How Proficient are CEE Seniors in their Abilities to Apply Sustainability Concepts during Design?

Although student understanding of sustainability concepts is crucial, it is becoming increasingly essential that engineers be able to apply this knowledge during the design process [1]. Given that completion of capstone design projects allows students to demonstrate their abilities to apply concepts and skills learned in previous courses, examination of project reports provides a unique opportunity to analyze the extent to which students apply sustainability knowledge during the design process. As a result, student design capabilities were measured by applying the Sustainable Design Rubric to capstone design project reports, as well investigating students' confidences in their design abilities (Figure 3.13).

Analysis of Capstone Projects Using the Sustainable Design Rubric

Comparison of Sustainable Design Expectations and Performances

Capstone project reports completed over the last decade were analyzed using the Sustainable Design Rubric, as per the previously outlined methods (Figure 3.8). Projects completed during Fall 2002, 2006, and 2011 were analyzed together to benchmark both project expectations and student sustainable design performance based on potential scores, earned scores, and sustainable design indexes (Table 3.18). Deficiencies in student sustainable design performance were captured by comparing potential and earned scores using matched-pairs *t*-tests. Results were used to identify strengths and weaknesses of students' design capabilities.

Sustainable Design Scores over Time

Given that some changes have been made to the CEE curriculum since 2002, including the inception of the undergraduate Environmental Engineering degree, changes in sustainable design scores over time were investigated. Project scores were identified as varying over time if F-statistics from ANOVA tables describing regression models were less than or equal to 0.05, indicating that variation in scores was larger than zero. However, these results were interpreted with caution, since changes in scores could be attributed to several factors besides curricular improvements, including more frequent sustainable design requests from sponsors and/or shifts toward inherently more sustainable project types.

To address the confounding factor of sponsor influence, multi-use trail projects sponsored by Forsyth County between 2004 and 2011 were examined as a special case. Essentially, each student group worked with the same project sponsor to design different sections of a network of multi-use trails. As a result, any potential fluctuations in sustainable design scores may be attributed to increased student design abilities, rather than changing sponsor expectations. As completed for general projects, regression analyses were used to capture any significant changes in project scores over time.

Sustainable Design Scores by Project Type

Multi-use trail projects were also examined to quantify the impact of project type on sustainable design scores. In addition to the fact that the project sponsor and design constraints remained relatively constant, multi-use trail projects were also unique because explicit goals, such as providing transportation alternatives, are explicitly sustainability-related. As a result, multi-use projects represent a “best case scenario” for sustainable design potential of capstone design projects. Average sustainable design indexes, potential scores, and earned scores for all multi-use trail projects and all capstone projects were compared using one-way ANOVAs to capture potential differences based on project type.

Student Perceptions of their Sustainable Design Abilities

Several items from the Student Sustainability Survey were used to capture students' perceptions of their sustainable design abilities. Following the surveying methods (Figure 3.10), students enrolled in Fall 2011 and Spring 2012 capstone courses were asked to rate their abilities to develop sustainable design, as well meet specific sustainability criteria during design. Sustainable design scores and survey responses were ultimately compared to provide a complete analysis of student design abilities (Figure 3.12).

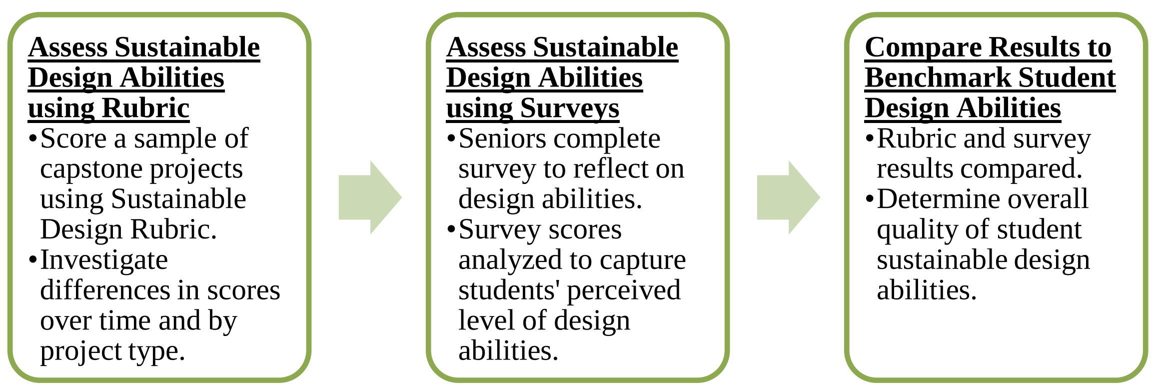

Figure 3.13. Method for evaluating students' sustainable design abilities.

Methods for Improving the Quality of Sustainability Education in CEE at Georgia Tech (Goal 2)

After the status of CEE sustainability education was systematically investigated, efforts were organized to improve student abilities to understand and apply sustainability concepts in design. A review of the literature demonstrated that active, experiential pedagogies are especially effective in promoting student learning [104], especially learning related to sustainability [118, 152]. As a result, a structured-inquiry, learning-cycle-based sustainability module was designed to guide students in becoming sustainable engineers. The module was integrated into CEE capstone and cornerstone design courses to investigate its impacts on student learning.

Question 2.1: How should an educational intervention be designed to be sensitive to the results of curricular and student knowledge assessments, as well as best practices in teaching and learning?

Review of literature, as well as assessment results (Research Questions 1.2 – 1.4), were used to guide design of a module to encourage students to learn about sustainability in an engineering context (Figure 3.14). Based on a review of best practices in teaching and learning in higher education (see *Chapter Two*), teaching "around the cycle," as well as active and collaborative pedagogies were identified as especially suitable for sustainability education. In addition, based on a review of sustainability and sustainable engineering (see *Chapter Two*), it was determined that students should at least have a fundamental understanding of four sustainability themes: economic sustainability, environmental sustainability, social sustainability, and sustainable engineering and assessment. Insights from curricular and knowledge assessments that guided development of the module included the need to provide students with a comprehensive and balanced perspective on sustainability. Additional results used to inform module design are summarized in *Chapter Eight*.

Using this information, a series of activities were developed in accordance with the Kolb learning cycle (Figure 2.13), and a module workbook was compiled to include all module materials (See *Chapter Eight*). The workbook was reviewed by faculty and graduate students in aerospace engineering, civil engineering, computer engineering, educational psychology, and environmental engineering to evaluate relevance and comprehensiveness of content, as well as suitability of module structure and pedagogies for undergraduate students. Specifically, the following questions were provided to reviewers to help them critique the module: (1) Is the content sufficiently comprehensive for undergraduate engineering students? (2) How is the content relevant for engineers involved in capstone design projects? (3) Can you suggest ways to increase students' self-navigation through the module? (4) How are pedagogies applied in the module appropriate for encouraging student learning about sustainability? Reviewer comments, such as requiring students to submit key activities and shortening required readings, were addressed during final workbook compilation. After implementations, some alterations were made to the module based on the Module Evaluation Survey (Table 3.19).

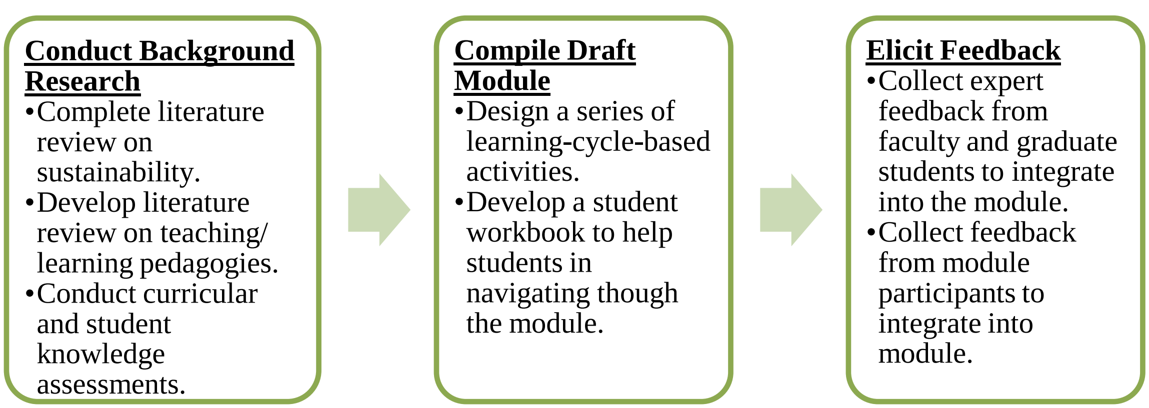

Figure 3.14. Method for designing an empirically- and theoretically-grounded sustainability module for CEE students.

Question 3.1: To what extent can integration of a sustainability module into a CEE capstone design course improve student sustainability knowledge?

Experimental Design

A quasi-experimental, untreated cohort control group design [215] was used to investigate the impacts of module completion on student learning in CEE capstone design courses (Figure 3.15). Since cohorts of students tend to have similar backgrounds and demographics [216], using an equivalent cohort as a control group is suggested to minimize selection biases that can be present in the nonequivalent comparison group design [215, 217]. Students enrolled in the Fall 2011 capstone design course were not exposed the module (control cohort), while students enrolled in the subsequent Spring 2012 capstone course completed all module sessions of (intervention cohort). Other than integration of the sustainability module, the intervention course was identical to the control course, including being led by the same two faculty instructors. Both changes in conceptual knowledge and improvements in sustainable design abilities were quantified.

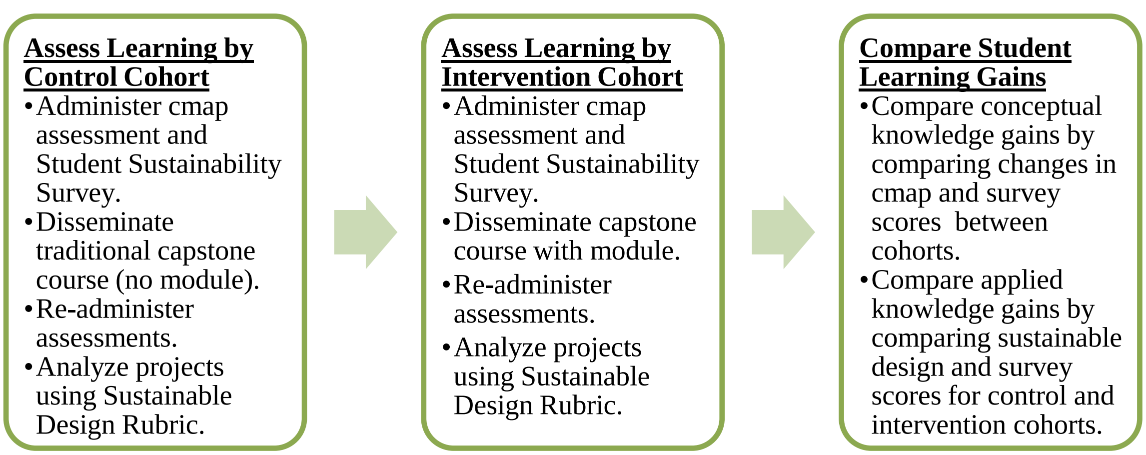

Figure 3.15. Method for assessing impacts of sustainability module on student learning in capstone design course.

Assessment of Changes in Conceptual Sustainability Knowledge

Sustainability knowledge was measured at the beginning and end of both the control and intervention courses (dependent pre-test and post-test samples) using the Student Sustainability Survey and concept map assessments, according to previously discussed methods (Figures 3.6 and 3.10). Using consensus scores, 2 (control group, intervention group) × 2 (pre-, post-scores) repeated measures ANOVA were employed to detect any significant trends (Table 3.21). Significant interactions between assessments and cohorts were used to infer impacts caused by presence or absence of the module. Pre- and post- responses to survey items asking students to rate their confidences in their abilities to discuss several aspects of sustainable development were compared separately for each cohort using McNemar tests (Table 3.22). To compare survey results between the two cohorts, Chi-Square tests were used to detect differences between the percentages of impacted students, defined as indication of less than six on the pre-survey and a six or seven on the post-survey (Table 3.23). Cmap and survey scores were compared to infer the overall effects of the module on student learning of sustainability concepts.

Table 3.21. Model of the ANOVA table used to compare main effects and interactions between pre- and post- cmap scores from two different cohorts.

		Cohort (Between Subjects)[1]	
		Cohort "X"	*Cohort "Y"*
Assessment (Within Subjects)	Pre-Cmap Score		
	Post-Cmap Score		

[1] Table used to compare scores between (1) capstone control and intervention cohorts, (2) cornerstone peer-lecture and peer-discussion cohorts, and (3) capstone intervention cohort and cornerstone cohorts.

Table 3.22. Model of 2×2 McNemar contingency table used to compare pre- and post-survey responses within a single cohort of students[1].

		Post-Survey	
		Positive Impact[2]	Non-Positive Impact[3]
Pre-Survey	Positive Impact[2]	a	b
	Non-Positive Impact[3]	c	d

[1]If McNemar statistic [$(b - c)^2/(b+c)$] is significant, then the marginal proportions of b and c are not the same [184]; [2]Defined as indicating a score of 1-5 on the pre-survey and a score of 6-7 on the post-survey; [3]Defined as indicating a score of 1-5 on both the pre- and post-survey or indicating a score of 6-7 on the pre- survey and a score of 1-5 on the post survey (rare).

Table 3.23. Model of 2×2 contingency table used to compare changes in survey scores between two different cohorts

		Cohort (Between Subjects)[1]	
		Cohort "X"	*Cohort "Y"*
Impact	Positive Impact[1]		
	Non-Positive Impact[2]		

[1]Table used to compare scores between (1) capstone control and intervention cohorts, (2) cornerstone peer-lecture and peer-discussion cohorts, and (3) capstone intervention cohort and cornerstone cohorts.

Assessment of Impacts on Sustainable Design Abilities

In addition to changes in conceptual knowledge, impacts of module participation on sustainable design abilities were also examined. Capstone design project reports generated by the control and intervention cohorts (post-test only sample) were evaluated using the Sustainable Design Rubric, as per previously discussed methods (Figure 3.8). A one-way ANOVA was used to detect any significant differences between sustainable design indicators, potential scores, and earned scores for the two cohorts. Pre- and post-responses to survey items asking students to rate their confidences in their abilities to meet several sustainable design criteria were compared separately for each cohort using McNemar tests (Table 3.22), while changes in pre- and post-scores between cohorts were quantified using Chi-Square tests (Table 3.23). Sustainable design and survey scores were simultaneously considered to judge the impact of the module on sustainable design abilities.

Question 3.2: To what extent can integration of a sustainability module into a CEE cornerstone design course improve student sustainability knowledge?

Seniors participating in the Spring 2012 implementation of the sustainability module (intervention cohort) indicated that the module would be more beneficial if incorporated into Civil Engineering Systems rather than Capstone Design. As a result, the sustainability module was implemented into two sections of Civil Engineering Systems (a.k.a cornerstone design) during Fall 2012, according to the methods outlined below.

Experimental Design

A quasi-experimental, one-group pretest-posttest design [215] was used to investigate the impacts of module completion on student learning in CEE cornerstone design courses (Figure 3.16). The module as a whole was nearly identical to the one developed for capstone design seniors, except for minor changes made based on feedback from seniors in the intervention cohort. Specifically, seniors requested less-structured sessions with more flexibility for group discussions when learning about sustainability concepts (Module Session 2, see *Chapter Eight* for more details). To determine if group discussions would indeed enhance learning, Section A of Civil Engineering Systems completed the sustainability module with a peer-lecture session, while Section B engaged in the module with a peer-discussion session. For both sections, the sustainability module was conducted during the first four weeks of the semester. Impacts of module participation, including any differences between module versions, on students' conceptual knowledge and sustainable design abilities were examined.

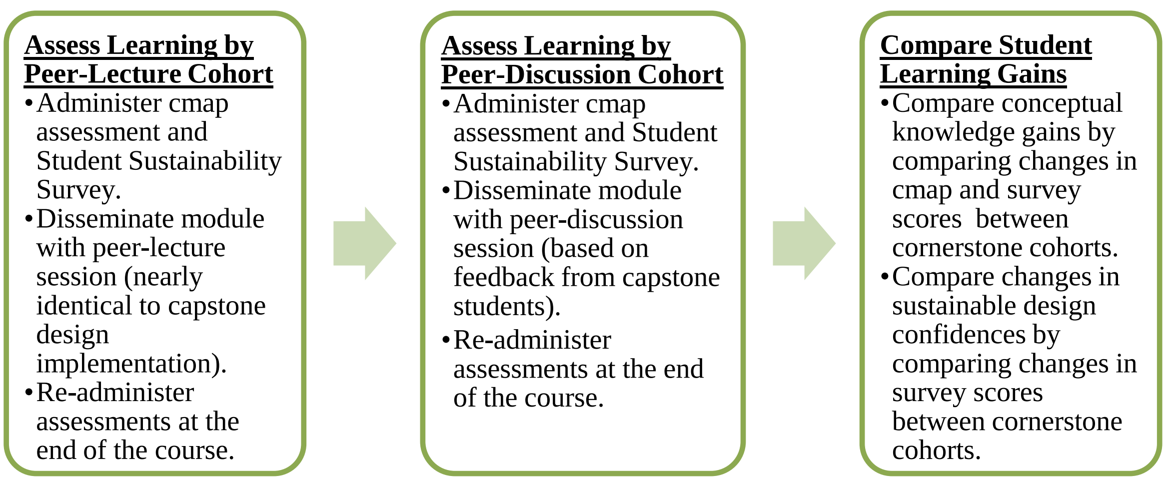

Figure 3.16. Methods for assessing impacts of sustainability module on student learning in Civil Engineering Systems.

Assessment of Changes in Conceptual Sustainability Knowledge

Conceptual sustainability knowledge was measured at the beginning and end of module implementations using the Student Sustainability Survey and concept-map-based assessments, according to previously discussed methods (Figures 3.6 and 3.10). Using consensus cmap scores, 2 (peer-lecture cohort, peer-discussion cohort) × 2 (pre-, post-scores) repeated measures ANOVA were employed to detect any significant trends (Table 3.21). Significant interactions between assessments and cohorts were used to identify meaningful differences in learning gains between cohorts. Survey items asking students to rate confidences in their abilities to discuss sustainable development and the related dimensions were also analyzed. Within a single cohort, McNemar's test was used to discern any differences between pre- and post-scores (Table 3.22). To compare changes in scores between cohorts, the percentages of impacted students were compared between control and intervention cohorts using Chi-Square tests (Table 3.23). Cmap and survey scores were compared to infer the overall effects of the module on student learning of sustainability concepts.

Assessment of Impacts on Sustainable Design Abilities

In addition to changes in conceptual knowledge, impacts of the module on sustainable design abilities were also examined. Pre- and post- responses to survey items asking students to rate their confidences in their abilities to meet several sustainable design criteria were compared separately for each the peer-lecture and peer-discussion cohorts using McNemar tests (Table 3.22), while changes in pre- and post-scores between cohorts were quantified using Chi-Square tests (Table 3.23).

Unlike capstone design seniors, cornerstone design students do not engage in a design project. Rather, students complete a semester project to analyze the sustainability of an existing infrastructure project (See section entitled "Cornerstone Design" above). While development of this project may indeed impact sustainable design abilities, the

Sustainable Design Rubric is not applicable to this type of project. As a result, only responses to items on the Student Sustainability Survey were used to infer module impacts on cornerstone students' sustainable design abilities.

Question 3.3: Is the sustainability module best suited for integration into CEE capstone or cornerstone design courses?

Finally, impacts of module participation on students' sustainability knowledge were also compared between capstone and cornerstone students. Specifically, cmap scores were compared using 2 (cornerstone cohort, capstone cohort) × 2 (pre-, post-scores) repeated measures ANOVA (Table 3.21), while responses to the Student Sustainability Survey were analyzed using Chi-Square tests (Table 3.23). Results were used to propose whether the module is best suited for integration in introductory or advanced CEE courses.

Summary of Assessments and Participants

Students enrolled in capstone and cornerstone courses between 2011 and 2012 were invited to participate in several assessments as part of this research study (Table 3.24). Of the 66 and 100 total students enrolled in the Fall 2011 and Spring 2012 capstone design courses, 58 and 95 participated in one or more assessments, respectively. Most capstone participants were male, (78.4%) civil engineering students (79.1%) from the US (83.6%). Of the 57 and 62 students enrolled in Section A and Section B of the Fall 2012 Civil Engineering Systems courses, 53 and 58 participated in one or more assessments, respectively. Most cornerstone participants were male (60.4%), civil engineering students (70.3%) from the US (77.5%). All methods involving human subjects were approved by the Georgia Tech Institutional Review Board (IRB).

Table 3.24. Summary of assessments implemented in capstone and cornerstone design courses.

Course	Semester	Treatment	Pre-Assessments	Post-Assessments
CEE 4090: Capstone Design	Fall 2011	No treatment; course was disseminated in traditional manner.	Student Sustainability Survey, Concept Maps	Student Sustainability Survey, Concept Maps, Sustainable Design Rubric
	Spring 2012	Integration of sustainability module; all other course elements same as Fall 2011.	Student Sustainability Survey, Concept Maps	Student Sustainability Survey, Concept Maps, Sustainable Design Rubric, Student Curriculum Survey, Module Evaluation Survey
CEE 3000: Civil Engineering Systems Cornerstone Design	Fall 2012, Section A	Integration of sustainability module; Session 2 comprised of peer lectures.	Student Sustainability Survey, Concept Maps	Student Sustainability Survey, Concept Maps
	Fall 2012, Section B	Integration of sustainability module; Session 2 comprised of peer discussions.	Student Sustainability Survey, Concept Maps	Student Sustainability Survey, Concept Maps

CHAPTER FOUR

Analyzing Student Perceptions of Sustainability Education

Chapter Overview

The goal of this chapter is to examine the current status of CEE sustainability education through analysis of student perceptions (Research Question 1.1; Table 1.2). While students are important stakeholders in sustainability education, studies examining their knowledge and beliefs are limited [9, 134, 218]. Students enrolled in CEE capstone design courses (Fall 2011 and Spring 2012, n = 153) were administered the Student Sustainability Survey (Appendix C) (See *Chapter Three* and Figure 3.10 for additional information on study methods). Results were used to address the following questions: (1) How interested are students in sustainability? (2) How confident are students in their understanding of sustainability? (3) What role does the CEE curriculum play in educating students about sustainability? (4) What strategies could improve the CEE curriculum? Findings will be synthesized to portray the student experience as it relates to sustainability education. In addition, student perceptions will later be compared to more objective assessments of the CEE curriculum (*Chapter Five*), student conceptual understanding of sustainability (*Chapter Six*), and student ability to apply sustainability principles in design (*Chapter Seven*).

Results

Student Interest in Sustainability

CEE students demonstrated overall interest in sustainability. In fact 70.6% of all respondents indicated strong interest (response of 6-7 on a 7-point scale) in sustainable development. Disaggregating the data by major, gender, and nationality revealed no statistically significant differences. In addition to being generally interested in sustainable development, students were also interested in many sustainability-related topics (Table 4.1). Specifically, out of more than 20 topics, students were most interested in sustainable infrastructure, sustainable transportation, and sustainable cities. In contrast, students were least interested in biological aspects of sustainability and links between sustainability and spirituality. Thus, students preferred sustainability topics more traditionally associated with CEE.

Student reflections on the impact of sustainability interest on important professional choices were varied. Only 40.5% of students indicated that their interest in sustainability greatly impacted their choice of academic major (response of 6-7 on 7-point scale), while 47.7% responded that their sustainability interest would greatly impact their future career goals. However, the proportion of environmental engineers indicating their sustainability interest to have greatly impacted their academic major ($\pi_{6\text{-}7}$ = 84.4%) and future career goals (($\pi_{6\text{-}7}$ = 87.5%) was significantly higher than the fraction of civil engineers indicating a high impact on academic major ($\pi_{6\text{-}7}$ = 28.9%) and career goals ($\pi_{6\text{-}7}$ = 37.2%) (Table 4.6). Thus, while nearly half of all CEE students consider sustainability interest when setting academic and career goals, this factor was most important to environmental engineers.

Table 4.1. Student interest in sustainability-related topics[1].

Survey Prompt: Indicate your level of interest in the following topics.	n[2]	π_{6-7} (%)
Sustainable infrastructure (water, waste, energy)	152	73.7
Sustainable transportation	153	73.2
Sustainable cities	152	65.1
Sustainable community development	151	64.2
Green buildings	153	62.1
Clean/renewable energy and energy efficiency	153	60.1
Pollution and environmental health	152	57.2
Natural resources management	152	50.0
Corporate responsibility and sustainability	152	46.7
Poverty alleviation and development	153	46.4
Environment and international development	149	45.6
Human nutrition, health and environment	152	44.1
Food security	146	43.2
Climate change	152	40.1
Conservation, biodiversity, ecosystems services	153	37.9
Global governance and sustainability	147	36.1
Globalization and international trade	146	34.9
Environmental justice	151	30.5
Environmental economics	146	28.1
Environmental policy	148	24.3
Environmental law	147	23.1
Environmental security	141	22.7
Spirituality, links to science and sustainability	143	19.6
Bioeconomy, biomaterials, and biorefineries	144	11.8

[1]Survey items adapted from [119].
[2]Number of students indicating that they knew enough about the topic to report their interest.

Student Knowledge of Sustainability

Conceptual Understanding of Sustainability

Students reflected on both the importance for engineers to conceptually understand sustainability, as well as their own levels of conceptual knowledge (Table 4.2). Scores revealed that most students perceived the overall ability to discuss sustainable development as being very important for engineers ($\pi_{6\text{-}7}$ = 77.8%), with the abilities to discuss the environmental ($\pi_{6\text{-}7}$ = 80.4%) and social ($\pi_{6\text{-}7}$ = 60.1%) aspects of sustainable development receiving the highest and lowest scores, respectively. In all cases, however, student confidences in their own abilities to discuss sustainable development, dimensional aspects of sustainability, and connections between dimensions were significantly lower than perceptions of importance for these same tasks ($p \leq 0.001$). Thus, while students recognized the importance of sustainability, they may have felt unequipped to discuss related topics in a professional capacity.

Student confidence differed based only on academic major (Table 4.6). Environmental engineering students were more confident in their abilities to discuss sustainable development ($\pi_{6\text{-}7}$ = 78.1%) than were civil engineers. Specifically, the proportions of environmental engineers who were extremely confident in their abilities to discuss environmental sustainability ($\pi_{6\text{-}7}$ =68.8%) and connections between the three sustainability dimensions ($\pi_{6\text{-}7}$ = 65.6%) were significantly higher than those for civil engineers ($\pi_{6\text{-}7}$ < 25.0%). Disaggregating the data by gender and nationality revealed no statistically significant differences.

Ability to Apply Sustainability Understanding

Students also provided insights into the importance for engineers to be able to apply sustainable design criteria, as well as into their own abilities to complete these tasks (Table 4.3). Most students indicated that developing sustainable solutions to engineering problems was very important overall ($\pi_{6\text{-}7}$ = 87.6%). More specifically, students indicated that protecting human health and well-being ($\pi_{6\text{-}7}$ = 92.8%), minimizing natural resource depletion ($\pi_{6\text{-}7}$ = 88.9%), and addressing stakeholder requests ($\pi_{6\text{-}7}$ = 87.6%) were among the most important sustainable design criteria for engineers. Few students indicated that they were very confident in their abilities to develop sustainable solutions to engineering problems overall ($\pi_{6\text{-}7}$ = 30.1%). In addition, only approximately half of students were very confident in their abilities to execute several sustainable design tasks, including protecting human health and well-being ($\pi_{6\text{-}7}$ = 54.9%) and using inherently safe and benign materials ($\pi_{6\text{-}7}$ = 48.4%). In contrast, even fewer students were very confident in their abilities to use innovative technologies ($\pi_{6\text{-}7}$ = 26.1%), life cycle analysis ($\pi_{6\text{-}7}$ = 29.4%), and environmental impact assessment tools ($\pi_{6\text{-}7}$ = 29.4%) to achieve sustainability. In all cases, student confidence was significantly lower than perceived importance ($p \leq 0.001$). Thus, while students acknowledge the importance of sustainable design skills, they also recognized potential to improved their own sustainable design abilities.

Student confidence ratings differed somewhat based on academic major (Table 4.6). Environmental engineers were more confident in their general abilities to develop sustainable solutions to engineering problems ($\pi_{6\text{-}7}$ = 53.1%) than were civil engineers ($\pi_{6\text{-}7}$ = 24.0%). More specifically, environmental engineers ($\pi_{6\text{-}7}$ = 90.6%) were more confident in their abilities to incorporate environmental impact assessment tools than were civil engineers ($\pi_{6\text{-}7}$ = 23.1%). No significant differences were found based on gender or country of origin.

Table 4.2. Student scores for importance of and confidence in abilities to discuss and/or engage in sustainable development.

Survey Prompt: The statements below are related to sustainable development (SD). Indicate how important you think it is for engineers to be able to complete the listed tasks. Also indicate how confident you are in your ability to complete the listed tasks.	$\pi_{6\text{-}7}$ (%)		χ^2 Test	
	Importance	Confidence	$\chi^2(1, n = 153)$	p
Develop sustainable solutions to engineering problems.	87.6	30.1	104.48	≤ 0.001***
Discuss the concept of SD.	77.8	49.0	27.27	≤ 0.001***
Discuss the connections between poverty, population, consumption, and environmental degradation.	60.1	32.7	23.18	≤ 0.001***
Discuss economic factors that affect SD.	72.5	32.0	50.35	≤ 0.001***
Discuss environmental factors that affect SD.	80.4	32.0	72.70	≤ 0.001***
Discuss social factors that affect SD.	60.1	33.3	22.07	≤ 0.001***
Evaluate an engineering design based on sustainability criteria.	86.3	34.6	85.30	≤ 0.001***

***$p \leq 0.001$

Table 4.3. Student scores for importance of and confidence in abilities to apply sustainable design criteria.

Survey Prompt: The statements below are related to sustainable design. Indicate how important you think it is for engineers to be able to develop designs that meet the listed criteria. Also indicate how confident you are in your ability to develop designs that meet the listed criteria.	$\pi_{6\text{-}7}$ (%)		χ^2 Test	
	Importance	Confidence	χ^2 (1, n = 153)	p
Addresses community and stakeholder requests	87.6	44.4	63.5	$\leq$ 0.001***
Considers local circumstances and cultures	81.7	41.8	35.0	$\leq$ 0.001***
Incorporates life cycle analysis	72.5	29.4	60.0	$\leq$ 0.001***
Incorporates environmental impact assessment tools	74.5	29.4	70.0	$\leq$ 0.001***
Incorporates systems analysis	73.2	32.7	53.8	$\leq$ 0.001***
Uses innovative technologies to achieve sustainability	73.2	26.1	67.8	$\leq$ 0.001***
Minimizes natural resource depletion	88.9	32.7	101.4	$\leq$ 0.001***
Prevents waste	83.7	37.3	68.9	$\leq$ 0.001***
Protects natural ecosystems	83.0	42.5	53.7	$\leq$ 0.001***
Protects human health and well-being	92.8	54.9	56.9	$\leq$ 0.001***
Uses inherently safe and benign materials	84.3	48.4	44.3	$\leq$ 0.001***
Uses renewable energy sources	72.5	32.7	48.8	$\leq$ 0.001***

***$p \leq 0.001$

Mediums for Student Learning about Sustainability

Given that CEE students perceived themselves to possess some understanding of sustainability, it was important to determine the experiences that most contributed to development of this knowledge (Table 4.4). Over half of students learned about sustainability "to a great extent" by participating in CEE courses, while approximately 40 percent indicated learning "a great extent" about sustainability through engaging with media sources. Other activities contributed to students' sustainability knowledge to a limited extent, including participating in an internship, undergraduate research, non-CEE courses, and clubs. Overall, the CEE curriculum is likely the primary source for student learning about sustainability.

Table 4.4. Extent to which students learned about sustainable development by engaging in curricular and extra-curricular activities.

Survey Prompt: Indicate the extent to which you have learned about sustainable development through:	*n*[1]	$\pi_{6\text{-}7}$ (%)
CEE courses at Georgia Tech.	153	52.3
Reading, listening to, or watching media sources	151	41.1
Participating in an internship or cooperative education experience.	86	30.2
Participating in undergraduate research at Georgia Tech.	68	22.1
Participating in non-academic activities.	131	17.6
Non-CEE courses at Georgia Tech.	149	16.1
Participating in clubs and organizations at Georgia Tech.	127	15.0

[1]Number of students indicating that they participated in the activity.

Quality of the CEE Curriculum

Since the CEE curriculum plays such an integral role in promoting student sustainability learning, the quality of these courses was investigated. More than half of respondents (59.5%) rated the quality of CEE sustainability education as either "very good" or "excellent," indicating that students were generally satisfied with the extent to which sustainability is integrated into their curricula. However, nearly a third of students (32.7%) rated the overall quality of sustainability education as "average," indicating that that there is room to further incorporate sustainability into the curriculum. Only a minority of students graded the curriculum as "marginal" or "poor" (7.9%).

Students also provided feedback on strategies for improving sustainability education (Table 4.5). A majority of students said that it was very important to provide more guidance on how to apply sustainability concepts to design in order to improve sustainability education. Students also indicated that it was very important to improve sustainability education through offering more courses that focus on sustainability concepts, providing more opportunities for students to discuss sustainability topics, and adding more sustainability concepts into existing classes. Thus, despite the acceptable quality of sustainability education, students generally supported many strategies for further integrating sustainability into the CEE curriculum.

Table 4.5. Student support of potential curricular reform strategies (n = 153).

Survey Prompt: Reflecting on your curriculum, indicate how important it is for your home department to improve sustainability education by:	$\pi_{6\text{-}7}$ (%)
Providing more guidance on how to apply sustainability concepts to design.	64.7
Offering more courses that focus on sustainability concepts and issues.	51.0
Providing more opportunities for students to discuss sustainability topics.	45.3
Adding more sustainability concepts into existing classes.	45.1

Table 4.6. Comparison of student interest in, knowledge of, and experiences related to sustainability by academic major (civil or environmental engineering).

Survey Item	$\pi_{6\text{-}7}$ (%)		Chi-Square Test		
	CivE Students (n = 121)	EnvE Students (n = 32)	$\chi^2(1, n = 153)$	p	d^1
Impact of SD interest on:					
Choosing a major	28.9	84.4	32.28	$\leq$ 0.001***	0.5
Setting future career goals	37.2	87.5	25.68	$\leq$ 0.001***	0.5
Confidence in abilities to:					
Discuss SD	41.3	78.1	13.72	$\leq$ 0.001***	0.3
Discuss environmental factors that affect SD.	22.3	68.8	25.07	$\leq$ 0.001***	0.4
Discuss connections between poverty, population, consumption, and environmental degradation.	24.0	65.6	19.96	$\leq$ 0.001***	0.4
Develop sustainable solutions to engineering problems	24.0	53.1	10.23	$\leq$ 0.001***	0.3
Incorporate environmental impact assessment tools in design	23.1	53.1	10.96	$\leq$ 0.001***	0.3

[1]Only significant differences with $p \leq 0.05$ and $d \leq 0.3$ reported, due to low proportion of environmental engineering, as compared to civil engineering students.
***$p \leq 0.001$

Discussion

Sustainability Interest

Investigating student sustainability interest is important because interest has been shown repeatedly to be a prerequisite for learning [219]. In the current study, a majority of students reported interest in sustainable development, as well as a number of related topics (Table 4.1). For CEE students in the current study, like students at the University of British Columbia (UBC) (n = 635) [119], student interest was highest for sustainable infrastructure, sustainable transportation, sustainable cities, sustainable community development, green buildings, and clean energy, while interest was lowest for links to science and sustainability and biological aspects of sustainability. Thus, there may be some commonalities between student sustainability interests across disciplines and institutions. Overall, student interest in sustainability may predispose them to successful learning about sustainability-related concepts.

Sustainability Knowledge

Students reported learning about many conceptual aspects of sustainability, although they indicated potential for more extensive learning (Table 4.2). Almost half of students felt equipped to discuss sustainable development, although only about a third were confident in their abilities to discuss the more specific economic, environmental, and social aspects of sustainability. Under-emphasis of the social aspects of sustainability has been documented for many students [118, 220]. This trend was somewhat true in the current study, with importance scores being lowest for the social dimension, as compared to the environmental and economic dimensions. In addition, student-provided confidence scores were significantly lower than importance scores for all sustainability concepts, indicating that efforts may be needed to improve sustainability knowledge.

Similarly, students report some learning about sustainable design criteria, although responses suggest potential for further learning (Table 4.3). Over two-thirds of students indicated that it is important for engineers to be able to fulfill each of the sustainable design criteria. In contrast, student confidence rankings were significantly lower, with incorporating life cycle analysis and using innovative technologies to achieve sustainability receiving the lowest scores. However over half of students were extremely confident in their abilities to protect human health and well-being, possibly because this is a fundamental tenant of engineering ethics [40], which all students learn about in the required Civil Engineering Systems course [179, 180]. Even so, lower confidence scores in comparison to importance scores suggests potential for improvement in student ability to engage in sustainable design.

Demographic Differences and Sustainability Interest and Knowledge

Academic Major

Academic major had a significant impact on sustainability interest and knowledge (Table 4.6). First, environmental engineers in the current study were more likely than civil engineers to consider their sustainability interests when choosing majors and setting career goals. Second, environmental engineers demonstrated increased confidences in their conceptual sustainability knowledge, including abilities to discuss sustainable development, environmental sustainability, and connections between sustainability dimensions, as compared to civil engineers. In addition, environmental engineers were significantly more confident than civil engineers in their abilities to develop sustainable solutions to engineering problems, especially through the use of environmental impact assessment tools. Differences in sustainability knowledge between civil and environmental engineering students has also been reported in the literature [135].

Several possibilities exist to account for the differences between the perceptions of civil and environmental engineering students. Given that interest is known to play a key role in the learning process [219], perhaps environmental engineers' (perceived) heightened awareness of sustainability concepts and principles stems from their keen interest in the topic. Alternatively, the differences may stem from contrasts in the students' curricula. However, the 2008 Self-Study Report [181], which includes instructors' subjective assessments of their courses' sustainability content, suggests that classes across all CEE specialties incorporate sustainability. In addition, it has been well-documented that all students are exposed to sustainability in the Civil Engineering Systems course [179, 180]. As a result, no convincing evidence is currently available that suggests curricular discrepencies are responsible for the difference in percieved knowledge between civil and environmental engineering students. However, it is likely that environmental engineering students are more interested in sustainability, which predisposes them to sustainability learning, or at least the perception of sustainability learning.

Nationality

Country of origin had no significant impact on student sustainability knowledge or interest. A similar study conducted with over 3000 participants from ten countries also found little difference between student-rated sustainability knowledge for students from developed and developing countries, although some evidence supported that US students may have less sustainability knowledge than students from European and Far Eastern countries [206]. The sample of CEE students in the current study was not large or diverse enough to compare the knowledge of students from individual countries, but it does support that US students perceive to understand sustainable development at the same level as international students.

Gender

Gender had no significant impact on student sustainability knowledge or interest. Similarly, both Azapagic et al. [206] and Earl et al. [133] also found awareness of sustainability to not vary by gender. However, based on anecdotal findings that sustainability topics are of particular interest to women, underscoring the importance of engineering for promoting sustainable development has been suggested as a strategy for increasing female participation in engineering [221-223]. While the current study does not show females to be more interested in sustainability than males, it does suggest that most CEE students in general are interested in the topic. Consequently, showcasing the connection between sustainability and engineering may be a successful tool for recruiting a variety of students.

Importance and Improvement of the CEE Curriculum

CEE Curriculum as Integral to Sustainability Education

It is clear that the CEE curriculum plays a critical role in educating students about sustainability (Table 4.4). In fact, it was the highest rated activity contributing to sustainability learning, compared to several other co- and extra-curricular activities. The only other significant source of learning was reading, listening, or watching media sources. Aminrad et al. [224] also found that mass media positively impacted environmental awareness among secondary school students in Malaysia, while Zsóka et al. [225] showed the media as being an important sustainability information source for university students in Hungary. While some media sources provide reputable information related to sustainability, others may be biased or without technical merit [226]. As a result, CEE courses may be the most credible source of sustainability learning for students. Given students' tendencies to consult media sources, instructors may consider promoting student learning by encouraging engagement with reliable media outlets. Overall, integration of sustainability concepts and skills into the CEE curriculum is critical, since it is the primary route for student learning.

Student Assessment of Sustainability Education

Given the potential impact of the curriculum on sustainability learning, it is important to carefully examine and evaluate its sustainability content. Most students completing the CEE curriculum indicated the quality of sustainability education to be very good (46.4%) or average (33.1%). While student feedback was generally positive, their evaluations of curricular quality are somewhat biased by their level of sustainability knowledge. For instance, students may provide high ratings, but they themselves may not truly grasp the broad and interconnected nature of sustainability. As a result, it is important in the future to supplement student scores with an independent and systematic curricular evaluation. For instance, STAUNCH® has been shown to be particularly useful for quantitatively evaluating the breadth and depth of a curriculum’s sustainability content [125]. STAUNCH® framework will be used to analyze the CEE curriculum in *Chapter Five*.

Using Student Feedback to Develop Reform Strategies

Even though students viewed sustainability education as acceptable, many acknowledged potential for improvement. Specifically, students supported strategies, such as providing more guidance on how to apply sustainability concepts to design, for improving sustainability education. One possible framework for introducing sustainability in the context of design is the 9 Principles of Sustainable Engineering [58]. Providing students with a generalizable (project non-specific) set of principles for sustainable design, as well as opportunities to exercise these principles in an academic setting, may encourage them to incorporate sustainability into their professional practices. While students suggested a slight preference for creating new classes, rather than modifying existing ones, experts have supported some level of horizontal integration to ensure that students do not view sustainability as isolated from traditional engineering tasks [102]. Finally, student desire to learn about sustainability through peer discussions may make experiential pedagogies, already shown to enhance sustainability learning [118], to be particularly effective in CEE. As demonstrated, student feedback can be used to inform and design effective plans for curricular reform.

Limitations

Several limitations to this study are acknowledged. First, student-provided confidence scores may over-estimate student knowledge. In fact, several authors have suggested that students' perceptions of their cognitive understanding are often greater than their actual knowledge [212-214]. Thus, students' abilities to understand and apply sustainability concepts may actually have been lower than suggested by student responses, which would suggest the need for more substantial curricular changes. Supplementary examination of student sustainability knowledge, perhaps using concept maps, should be completed to gain a more holistic view of student understanding (see *Chapter Six*). Second, student assessment of the quality of sustainability education assumed that students adequately understood the complex and interrelated nature of sustainability. While student understanding may not have been perfect, it is believed that completion of a mandatory Civil Engineering Systems course with extensive sustainability content [179] equipped students to make valid judgments about CEE sustainability education. However, final assessment of the curriculum should not be made only based on student experiences. Rather, use of systematic tools for curricular evaluation, such as STAUNCH®, is suggested to supplement student perceptions (see *Chapter Five*). Despite these limitations, student perceptions of sustainability education are important to consider because they are most intimately aware with curricular content and they are the ones who the curriculum is designed to benefit.

Summary and Conclusions

A study was conducted to provide a student perspective of sustainability education in CEE at Georgia Tech through analysis of responses from the Student Sustainability Survey, which was designed to capture student interest in, knowledge of, and learning experiences related to sustainability. The following conclusions were made based on the results.

1. Most CEE students were very interested in sustainable development.
2. Student ratings on their own abilities to understand and apply sustainability concepts were significantly lower than their ratings on the importance for engineers to possess these same abilities, which suggests potential for improvements in student learning.
3. While students reported equally low confidence ratings for their abilities to discuss the three sustainability dimensions, they viewed environmental and social dimensions as the most and least important for engineers, respectively.
4. Students learned most about sustainability through CEE courses, as compared to other curricular and extra-curricular activities, which underscores the importance to ensure curricular quality.
5. While students were generally satisfied with CEE sustainability education, they supported implementation of several strategies that could further improve the curriculum, especially providing more guidance on applying sustainability during design.

Overall, student insights substantiate departmental efforts to incorporate sustainability into the curriculum, although responses also suggest the potential for future improvements. No matter the strides made in sustainability education, it is likely that reform and assessment efforts will need to be continuous, due to the evolving and subjective nature of sustainability itself [197, 227, 228]. As a result, other departments and programs are encouraged to take advantage of student perceptions surveys, which offer a relatively quick and inexpensive examination of sustainability education. In addition, incorporating student surveys into assessment procedures also gives students a valuable opportunity to critically reflect on their own knowledge and experiences, which is an important component of the learning process [229]. Independent of the assessment measure employed, efforts to implement and ensure the efficacy of strategies to incorporate sustainability concepts and principles into undergraduate engineering curricula are paramount for training future engineers to design and implement projects in a sustainable manner.

CHAPTER FIVE

EXAMINING THE SUSTAINABILITY CONTENT OF THE CEE CURRICULUM

Chapter Overview

The goal of this chapter is to analyze the current extent to which sustainability is integrated into the CEE curriculum at Georgia Tech (Research Question 1.2; Table 1.2). After collecting and analyzing course syllabi, STAUNCH® (Table 3.5 - 3.4) was used to examine the content and quality of sustainability education (see Appendix G for final report). In addition, student reflections on the CEE curriculum were gathered primarily through administration of the Curriculum Sustainability Survey (Table 3.19) (Appendix D), although some items from the Student Sustainability Survey (Appendix C) were also used (see *Chapter Three* and Figure 3.11 for additional information on study methods). STAUNCH® results and student perceptions were used to (1) examine which sustainability dimensions CEE courses currently over- or under-emphasize, (2) identify key courses contributing to sustainability education, and (3) judge the overall quality of the curriculum. Overall, this study provides insights for improving sustainability education both in CEE at Georgia Tech and broadly.

Results

STAUNCH® Analysis

The STAUNCH® system was used to evaluate sustainability content of the undergraduate CEE curriculum. Of the 44 total CEE courses examined, syllabi from 61% provided evidence of contribution to sustainability education. These syllabi were further analyzed to characterize topics and dimensions emphasized by the curriculum, quantify overall quality metrics, and identify exemplary courses.

Content Analysis

While many CEE courses contributed to sustainability education, it is likely that most content related to the environmental dimension. In fact, based on syllabi examination, 62% of all sustainability-related content fell within the environmental dimension, while only 12% and 3% fit within economic and social categories, respectively. Incorporation of concepts and skills defining the cross-cutting dimension was substantial (24%), although still considerably less than the environmental dimension. Overall, the sustainability content of the CEE curriculum was largely unbalanced due to over-emphasis of environmental topics.

Despite the emphasis on environmental sustainability, a variety of sustainability topics were emphasized in undergraduate CEE courses (Figure 5.1). Specifically, nearly all environmental topics were addressed, although resource use (22%), pollution (17%), products/services (14%), and land use (14%) were the most prevalent. Resource efficiency (eco-efficiency) was the only environmental topic not discussed within the syllabi. Evidence was also found for incorporation of the cross-cutting dimension, including systems (19%), holistic (7%), and long-term (7%) thinking skills. In addition, substantial contributions to the cross-cutting dimension were derived from CEE courses being offered to or through other academic schools (disciplinarity, 45%) and explicit discussion of the sustainable development paradigm (22%). Within the economic dimension, only three of the seven topics were addressed, including finances (56%), resource exhaustion (33%), and production/consumption patterns (11%). Similarly, most concepts within the social dimension were absent, although human rights, employment, and equity/justice accounted for equal parts (33%) of the social sustainability content.

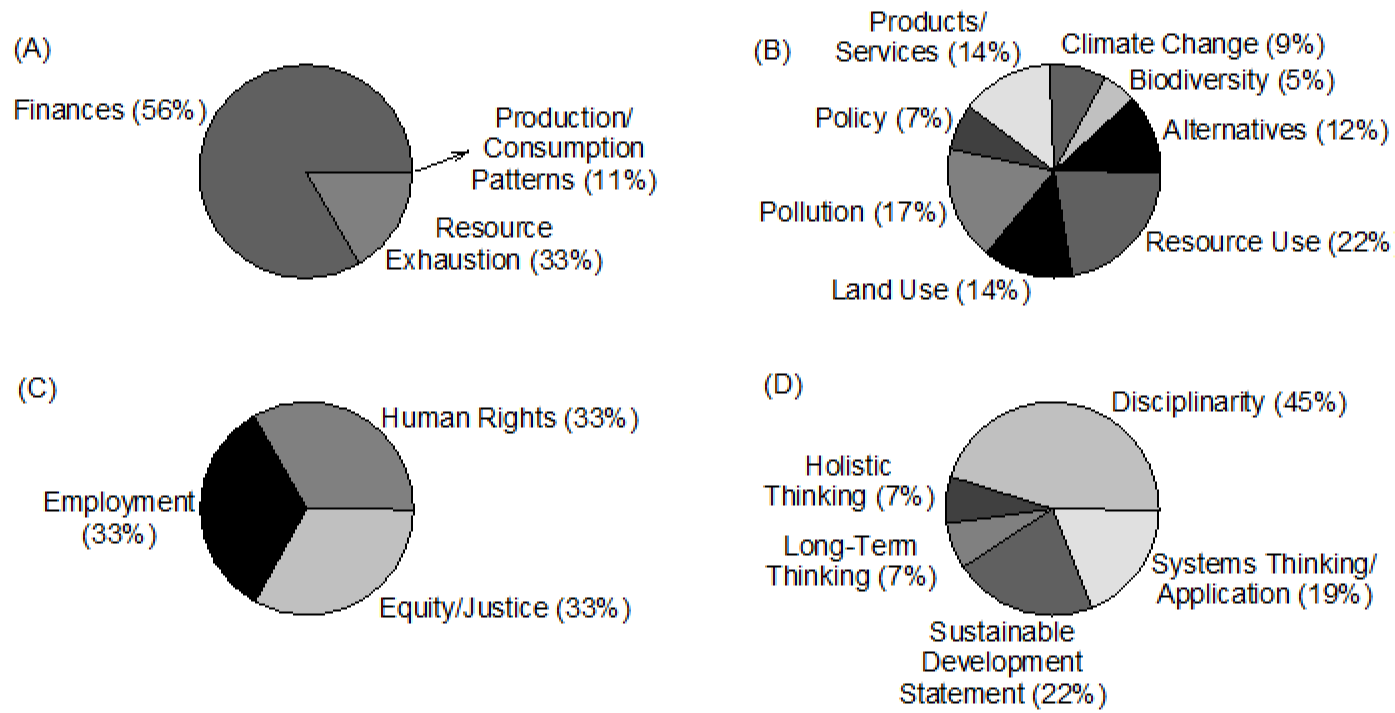

Figure 5.1. Incorporation of key topics within (A) economic, (B) environmental, (C) social, and (D) cross-cutting sustainability dimensions into the CEE curriculum at Georgia Tech.

Overall Quality of Sustainability Education

The overall quality of CEE sustainability education was quantified through the contribution and strength metrics provided by the STAUNCH® system. Using a proprietary formula, the contribution metric for CEE courses was 1.36, which falls within the "medium" range (Table 3.6). While this represents substantial progress towards quality sustainability education, it is likely that the over-emphasis of courses on the environmental dimension, at the expense of the economic and social ones, prevented the contribution metric from being higher. With 71, 19, and 10% of covered topics being rated as a 1, 2, and 3, respectively (Table 3.5), the strength of the contribution was computed to be "medium" (1.39). The strength metric could be further improved by more extensively addressing key concepts in class. Overall, the contribution and strength metrics suggest that while sustainability education could be further improved, the current curriculum does in some capacity foster student learning about sustainability.

Key Courses

Although most courses exhibited contribution metrics within the "low" or "very low" ranges (Table 5.1), several courses had scores within the "medium" range or higher (Table 3.6). For instance, Construction Engineering and Management exhibited a "high" contribution metric (3.33) through consideration of all sustainability dimensions. Civil Engineering Systems and Environmental Systems Design also demonstrated "high" contribution scores (2.00), although syllabi lacked evidence that the social dimension was addressed through class activities. Finally, Sustainable Engineering showed a "medium" contribution score (1.44), with the syllabus suggesting that all four dimensions were addressed in some capacity. Overall, among the CEE courses examined, these courses holistically presented sustainability in a multi-dimensional manner.

Table 5.1. CEE courses with "medium" or "high" contributions to sustainability education.

	Contribution Metric	Economic (%)	Environmental (%)	Social (%)	Cross-Cutting (%)
Construction Engr	3.33	40	20	20	20
Civil Engr Systems	2.00	14	14	0	71
Env Systems Design	2.00	33	33	0	33
Sustainable Engr	1.44	8	46	8	38

Despite the emphasis of the curriculum as a whole on environmental sustainability, several courses incorporated one or more under-emphasized dimensions (Table 5.2). For instance, seven courses captured non-disciplinary aspects of the cross-cutting dimension, including Capstone Design, which encouraged students to embrace the sustainable development paradigm during development of their semester projects. In addition to the four courses that demonstrated "medium" to "high" contribution metrics, Construction Operations and a seminar course introduced students to the economic aspects of sustainability. Of the 44 total courses evaluated, only three syllabi showed evidence of integration of social sustainability concepts, including Construction Engineering & Management, Hazardous Substance Engineering, and Sustainable Engineering. Thus, a limited number of courses have initiated efforts to present the multi-dimensional aspects of sustainability.

Table 5.2. CEE courses incorporating non-environmental sustainability concepts.

Cross-Cutting Dimension[1]		Economic Dimension		Social Dimension	
Course	%	Course	%	Course	%
Civil Engr Systems	71	GTS 2000 Seminar	100	Construction Engr	20
Infrastructure Rehab	50	Construction Ops	50	Hazardous Sub Engr	17
Env Systems Design	33	Construction Engr	40	Sustainable Engr	8
Sustainable Engr	38	Env Systems Design	33		
EnvE Systems	25	Civil Engr Systems	14		
Capstone Design	25	Sustainable Engr	8		
Construction Engr	20				

[1]Courses contributing only through disciplinarity include Introduction to Engineering Graphics, Statistics and Applications, Composite Materials and Processes, and Mechanical Behavior of Composites.

Student Perspective on Sustainability Education

While STAUNCH® provides a systematic procedure for characterizing a curriculum's sustainability content, the validity of results relies on the accuracy of published course materials. Situational factors, such as student proficiency and time constraints, may preclude an instructor from strictly following the course syllabus. To address this limitation, capstone design students, having recently completed most of the CEE curriculum, were recruited to rate the quality of the curriculum and incorporation of STAUNCH® topics into their CEE courses.

Content Analysis

Students conveyed that CEE courses most extensively addressed the cross-cutting and environmental sustainability dimensions (Table 5.3). In fact, 45% of student responses indicated that cross-cutting topics were incorporated "to a great extent" within the curriculum (responses of 6-7 on seven-point scale), especially long-term thinking, sustainable development, and communication. In addition, 37% of responses showed that environmental topics were significantly integrated into the curriculum, including pollution, climate change, and resources use. Economic and social concepts were less incorporated into CEE courses.

Table 5.3. Student-provided rankings on the extent of incorporation of STAUNCH® sustainability topics into the CEE curriculum at Georgia Tech (n = 82).

Economic Topics	$\pi_{6\text{-}7}$ (%)	Environmental Topics	$\pi_{6\text{-}7}$ (%)
Resource exhaustion	38	Pollution	54
Accountability	30	Climate change	49
Finances	24	Resources use	45
Developmental economics	18	Products/Services	39
Production/Consumption Patterns	17	Alternatives	38
Overall[1]	22	*Overall*[1]	37
Social Topics	$\pi_{6\text{-}7}$ (%)	**Cross-Cutting Topics**	$\pi_{6\text{-}7}$ (%)
Education	41	Long-term thinking	65
Health	27	Sustainable Development	59
Politics	21	Communication	56
Population	18	Responsibility	55
Diversity	17	Systems thinking	54
Overall[1]	16	*Overall*[1]	45

[1]Calculated as (Number of 6-7 rankings within dimension/total number of rankings within dimension) * 100.

Overall Quality

Reflecting on the CEE curriculum as a whole, students provided insights on the quality of and suggestions for improving sustainability education. A majority of students classified the sustainability content as very good (46.4%) or average (32.7%), while only a few students (13.1%) provided responses of excellent. Many students indicated that it was very important to improve sustainability education through providing more guidance on how to apply sustainability concepts to design ($\pi_{6\text{-}7}$ = 59.5%). See *Chapter Four* for more results from the Student Sustainability Survey.

Key Courses

Students were prompted to rank the top five courses in the CEE curriculum that they viewed as most addressing sustainability (Table 5.4). Overall, students reported 21 different courses as incorporating sustainability concepts. Based on raw total scores (rank of 1 received score of 5 and a rank of 5 received score of 1), students viewed Civil Engineering Systems and Capstone Design as most integral to sustainability education. However, both of these courses were required for all CEE students, so it is possible that their high raw scores resulted due to the large number of enrolled students. Based on total scores normalized by number of enrolled students during the 2010-2011 academic year, Environmental Impact Assessment was shown to be most valuable to sustainability education, although Civil Engineering Systems and Capstone Design were still ranked within the top three.

Table 5.4. CEE courses most contributing to sustainability education, according to students (n = 84).

Rank	By Raw Score[1]	By Normalized Score[2]
1	Civil Engineering Systems	Environmental Impact Assessment
2	Capstone Design	Civil Engineering Systems
3	Environmental Engineering Principles	Capstone Design
4	Environmental Engineering Systems	Air Pollution Engineering
5	Environmental Impact Assessment	Environmental Engineering Systems

[1]Students ranked the top five CEE courses contributing to sustainability education. Courses ranked as first received a score of five, while courses ranked as fifth received a score of one. Scores were summed for each course.
[2]Raw score for each course was divided by the number of students enrolled in that course during the 2011-2012 academic year to eliminate any unfair advantage of courses with required or high enrollment.

Discussion

Comparing STAUNCH® Assessment with Student Perceptions

Content Analysis based on Sustainability Dimensions

Both the formal STAUNCH® assessment and student survey responses aligned with regards to sustainability dimensions most integrated into the CEE curriculum. According to weighted percentages computed by STAUNCH® (Table 5.1), sustainability content was dominated by environmental concepts, followed by those from cross-cutting, economic, and social dimensions. Similarly, mean student scores describing extent of consideration within the curriculum were highest for the environmental and cross-cutting dimensions, while being the lowest for the social dimension. Overall, results from both curricular assessments support that concepts and skills comprising the environmental and cross-cutting categories were most prevalent, while those from the economic and social dimensions were somewhat neglected (Table 5.3).

Content Analysis based on Key Topics

Identification of key concepts most incorporated into the curriculum were similar based on STAUNCH® results (Figure 5.1) and student-provided ratings (Table 5.3), although some discrepancies existed (Table **5.5**). Within the economic category, finances, resource exhaustion, and production/consumption patterns were suggested to be addressed within CEE courses by both STAUNCH® and undergraduates. However, accountability was absent from the STAUNCH® report, while students indicated this topic to be the second most emphasized economic topic. Within the environmental dimension, both assessments supported that resources use, pollution, and products/services were commonly discussed in courses. Student responses suggested that land use topics were less emphasized than proposed by STAUNCH®, while climate change topics were more extensively addressed. Consensus existed that sustainable development (as a concept), systems thinking, holistic thinking, and long-term thinking were incorporated into the curriculum. Although STAUNCH® did not detect curricular emphasis on communication and responsibility, students reported that these topics are included in CEE courses. The biggest differences, however, are for the social dimension, in which the top five concepts identified by students were absent from the STAUNCH® report. While discussed discrepancies likely result due to course syllabi not accurately capturing all aspects of classroom activities, STAUNCH® and student-generated scores related to consideration of key concepts were largely similar, with the exception of those from the social dimension.

Table 5.5. Most emphasized curricular topics according to STAUNCH® and student surveys.

	STAUNCH® Assessment	Student Assessment
Economic Topics[1]	• Finances, Resource use, Production/consumption patterns	• Resource exhaustion, Accountability, Finances, Developmental economics, Production/consumption patterns
Environmental Topics	• Resources use, Pollution, Desertification, Products/services, Alternatives	• Pollution, Climate change, Resources use, Products/services, Alternatives
Social Topics[1]	• Employment, Equity, Health	• Education, Health, Politics, Population, Diversity
Cross-Cutting Topics	• Disciplinarity, Sustainable development, Systems thinking, Holistic thinking, Long-term thinking	• Long-term thinking, Sustainable development, Communication, Responsibility, Systems thinking

[1]STAUNCH® report only indicated that three topics from these dimensions were addressed in the curriculum.

Overall Quality of Sustainability Education

Both STAUNCH® and student experiences suggest that the overall quality of sustainability education in CEE at Georgia Tech is positive with potential for improvement. The contribution and strength metrics computed by STAUNCH® were both in the “medium” range, which substantiates intentional efforts to expose students to sustainability [181], but suggests that additional reforms could further promote student learning. Similarly, only 13% of students indicated that the overall quality of sustainability education was excellent, and many students supported various reform efforts to improve sustainability integration. Overall, it is clear that CEE is making strides towards educating sustainability-conscious engineers.

Key Courses

Several similarities and differences existed between key courses identified by STAUNCH® analysis (Table 5.1) and student perceptions (Table 5.4). Based on both assessments, it is clear that Civil Engineering Systems was an indispensable component of sustainability education, since it earned a “medium” STAUNCH® contribution score and was consistently highly ranked by students based on its incorporation of sustainability. Capstone design was also highly-ranked by students and was shown to present sustainability in a multi-dimensional fashion based on STAUNCH® analysis. However, Construction Engineering & Management, Environmental Systems Design, and Sustainable Engineering all received “medium” or “high” STAUNCH® contribution scores, while ranking 12th, 8th, and 10th, respectively, based on student rankings by normalized course enrollment numbers. Possible explanations for these differences may be that the course syllabi over-state the sustainability concepts actually presented in classes or students may not make connections between course content and sustainability.

Many of the courses ranked highly by students based on sustainability content (Table 5.4) were found by STAUNCH® to only consider environmental sustainability.

Specifically, Environmental Impact Assessment, Air Pollution Engineering, and Environmental Engineering Systems all received “very low” or “low” contribution scores primarily because the syllabi only provided evidence that environmental topics were discussed in class. However, these courses were consistently ranked highly by students based on their overall sustainability content. While this may simply suggest discrepancies between course syllabi and classroom instruction, it is possible that this supports that students fail to grasp the multi-dimensional nature of sustainability, as has been suggested by other authors [118, 220].

Implications for Civil and Environmental Engineering at Georgia Tech and Abroad

Based on the STAUNCH® assessment of the CEE curricula at Georgia Tech, several principles are highlighted for successful integration of sustainability into undergraduate curricula. First, as indicated by different authors [99, 102], incorporating sustainability concepts broadly within existing courses in conjunction with technical content (horizontal integration) may encourage students to view sustainability in a systemic and holistic manner, as well as promote sustainability in their professional practices. Indeed, with 61% of all courses incorporating some aspect of sustainability, CEE at Georgia Tech has made significant efforts to adapt the horizontal integration strategy. In addition, like students at UBC [119] and Shandong University [120], CEE students at Georgia Tech were supportive of incorporating sustainability into their curricula. However, just as was demonstrated for students at Shandong University [120], Georgia Tech CEE students showed the least support for integrating sustainability into existing classes (Table 4.5). As a result, administrators and instructors may need to be aware of potential student resistance when attempting to broadly incorporate sustainability into traditional courses.

Second, incorporation of sustainability content across a curriculum must be balanced among all sustainability dimensions, as supported by [22]. However, the results of both the STAUNCH® and student surveys suggest that the environmental dimension is grossly over-emphasized, as compared to the economic and social dimensions. Similarly, many stakeholders, including students and university leaders from a variety of institutions, tend to over-emphasize the environmental dimension of sustainability [9, 118, 120, 134, 136, 230]. Thus, there is a widespread need to encourage balanced integration of sustainability into undergraduate curricula.

Third, a "stronger" integration of balanced sustainability concepts into courses is advised. For instance, casually mentioning the connection between a technical concept and sustainability (weak integration) may not resonate with students, while extensive discussions about or applications of sustainability concepts (strong integration) may become integrated into students' long-term memories. For the case of Georgia Tech, the strength metric was "medium" (1.39). Consequently, it is suggested that efforts be made to demonstrate more deeply the connections between technical and sustainability content, perhaps by employing active and experiential pedagogies (e.g. project-based learning, case study, evaluation, role-playing, etc) shown by Segalàs et al. [118] to encourage integration of sustainability concepts into students' knowledge networks.

While applying the principles discussed above may aid in transforming undergraduate engineering curricula, it is first essential to systematically benchmark a curriculum's incorporation of sustainability content, including strengths and weakness, as indicated by Lozano and collaborators [21, 125, 231, 232]. The current study shows that both STAUNCH® and student perceptions surveys are appropriate for conducting such curricular assessments. For instance, both assessment techniques substantiated claims that sustainability has been integrated into the curriculum [181], nonetheless both methods also highlighted the capacity for further improvement. More specifically, both STAUNCH® and student perceptions' concurred that the environmental dimension was over-emphasized in courses. However, some slight discrepancies were identified related to the specific topics that were covered in CEE courses, especially within the social dimension. Thus, STAUNCH® assessments and perceptions survey may be used to gauge the overall status of a curriculum's sustainability content; however, the use of both methods may be necessary to provide a more detailed and holistic picture of the specific sustainability content of a curriculum.

Incorporating sustainability into undergraduate curricula (using the three principles outlined above and one or both of the curricular assessment methods demonstrated in this study) is critical. Not only can such reforms lead to the evolution of sustainability-conscious engineers [1], but student exposure to sustainability-related content in the classroom may also lead to them to engage in pro-sustainability-related actions in their personal lives [225, 233]. As a result, efforts to reform undergraduate engineering curricula may facilitate the development of citizens that consider sustainability in both their professional and personal lives.

Limitations

Several limitations to this case study are acknowledged. First, the STAUNCH® analysis relied only on published course syllabi from the CEE ABET Self-Study Report [181]. As is suggested by the creator of STAUNCH® [125] and other authors [194], the validity of the analysis relies on the accuracy and comprehensiveness of published course materials. To address this limitation, seniors having nearly completed the curriculum were asked to reflect on how extensively the 40 key concepts were addressed in their CEE classes. While some discrepancies were identified, the overall balance of sustainability education between the four dimensions was similar between the STAUNCH® analysis and student perceptions. In addition, both forms of assessment suggested that there was still potential to improve the undergraduate curriculum. However, it is acknowledged that there are shortcomings associated with asking students to recall the content of courses that they may have completed several years prior. While this may impact the magnitude of the responses, it would not likely have an impact on the relationships among sustainability dimensions, since students would most remember those topics that were extensively covered and would forget those that were only mentioned.

Summary and Conclusions

A study was conducted to evaluate sustainability education in CEE at Georgia Tech for the purpose of informing curricular reforms. To characterize the sustainability content of the curriculum, both an independent STAUNCH® assessment and an internal student evaluation were completed. The following conclusions were made based on the results.

1. With over 60% of CEE courses incorporating one or more related topics, sustainability was broadly integrated into the curriculum.
2. Despite this broad integration, the curriculum significantly over-emphasized the environmental dimension, while grossly under-emphasizing the social dimension.
3. With the curriculum yielding "medium" contribution and strength metrics, it is clear that efforts have been made to incorporate sustainability into the curriculum, although there is potential for further improvements.
4. Despite some discrepancies, student reflections largely validated the STAUNCH® analysis, especially the over- and under-emphasis of the environmental and social dimensions, respectively, as well as the potential for future improvements.

While the current study focuses on sustainability education in CEE at Georgia Tech, several insights can improve the quality of sustainability education abroad. Specifically, when designing a curriculum, intentional efforts are needed to ensure that sustainability content is distributed broadly across all (or most) courses in a manner that equally emphasizes the economic, environmental, and social aspects of sustainability, as well as those topics that are multi-dimensional (or cross-cutting). In addition, it is imperative that sustainability topics be extensively (or strongly) discussed and applied in courses to ensure that students retain the information needed to apply sustainability in their professional practices. Current undergraduate students will soon be responsible for local and global development projects that will impact both humans and the environment. Thus, combating current trends in poverty, resource consumption, and environmental degradation using a sustainable development paradigm necessitates that undergraduate curricula properly equip future engineers to engage in sustainable design.

CHAPTER SIX

ANALYZING UNDERGRADUATES' CONCEPTUAL SUSTAINABILITY KNOWLEDGE

Chapter Overview

The goal of this chapter is to examine the extensiveness of CEE students' conceptual understanding of sustainability (Research Question 1.3; Table 1.2). In addition to reflecting on their conceptual knowledge through completion of the Student Sustainability Survey (Table 3.19; See *Chapter Four* for results), students enrolled in CEE capstone design courses (Fall 2011 and Spring 2012, n = 144) were prompted to create cmaps on the focus question: What is sustainability? (Figure 3.6). Student-generated cmaps were then scored using three approaches by two expert judges (See *Chapter Three* and Figure 3.12 for additional information on study methods). Capstone design students were targeted for this study because they had completed most of their CEE coursework and examination of their knowledge may reveal strategies for supplementing the current curriculum. Results were used to address the following questions: (1) What do survey results and cmap scores suggest about the overall quality (including knowledge depth, breadth, balance, and connectedness) of CEE student sustainability knowledge? (2) How does sustainability knowledge differ between different demographic groups? (3) What insights can survey and cmap results provide for the design of educational interventions to improve student sustainability knowledge?

Results

Survey-Based Assessment of Conceptual Knowledge

Students were asked to reflect on their conceptual understanding of sustainability through completion of the Student Sustainability Survey (Table 4.2). Slightly less than half of seniors were “extremely” confident in their abilities to discuss the overall concept of sustainable development, while less than 35% were “extremely” confident in their abilities to discuss dimensional aspects of sustainability. Although CEE students as a whole generally lacked confidence in their sustainability knowledge, environmental engineering students were especially more confident than civil engineers in the abilities to discuss the overall concept of sustainable development, as well as environmental sustainability and the connections between sustainability dimensions. Nevertheless, survey results suggest that overall CEE student sustainability knowledge was somewhat limited (See *Chapter Four* for additional details on survey results).

Concept-Map-Based Assessment of Conceptual Knowledge

Students enrolled in capstone design during the Fall 2011 and Spring 2012 semesters were prompted to create sustainability-focused cmaps. Student-generated constructs were analyzed using the traditional, holistic, and categorical scoring methods to extract information about students’ conceptual sustainability knowledge.

<u>Traditional Approach</u>

The traditional method revealed that student sustainability knowledge was similar for Fall and Spring 2012 capstone design cohorts (Table 6.1). No significant differences were found between the mean number of concepts, which is an indicator of knowledge breadth, included by students from both semesters (M = 13.4). Similarly, the knowledge depth, quantified by the highest level of hierarchy, was not statistically different for the two groups (M = 3.4). The numbers of cross-links, which represents knowledge, were also similar for both cohorts (M = 2.4). By applying weightings of 1, 5, and 10 to the number of concepts, highest level of hierarchy, and number of cross-links, respectively, the mean total traditional scores for cohorts were also comparable (M = 51.6). Thus, the traditional method indicated no differences between the content (number of concepts and highest level of hierarchy) and structure (number of concepts) of student cmaps.

Table 6.1. Analysis of sustainability concept maps generated by capstone design students using the traditional scoring method [mean (standard deviation)][1].

	Fall 2011	Spring 2012	Combined	ANOVA	
	(*n* = 51)	(*n* = 93)	(*n* = 144)	$F(1, 142)$	p
Number of concepts	13.5 (6.0)	13.3 (6.1)	13.4 (6.1)	0.032	0.858
Highest level of hierarchy	3.7 (1.9)	3.3 (1.2)	3.4 (1.5)	3.478	0.064
Number of cross-links	2.2 (2.6)	2.4 (2.9)	2.4 (2.8)	0.191	0.663
Total	52.1 (25.6)	51.4 (30.6)	51.6 (28.8)	0.107	0.898

[1]Some variables in this table exhibit kurtosis/SE > 3.29. Since no significant relationships were found, rate of Type I error not relevant. Relationships still not significant with nonparametric Kruskal-Wallis test.

Holistic Approach

Like the traditional method, the holistic approach indicated few differences between CEE seniors from different cohorts (Table 6.2). Comprehensiveness, which captures knowledge breadth and depth, was significantly higher for Fall 2011 students (M = 1.4), as compared to Spring 2012 students (M = 1.2). However, no statistical differences were found for the organization (indicator of knowledge connectedness) (M = 1.3) or correctness sub-scores between the groups (M = 2.9). Despite the slight difference in comprehensiveness scores, no significant differences were demonstrated for total holistic scores based on cohort (M = 5.4). Thus, while Fall 2011 students may have constructed more comprehensive cmaps, the overall quality of their sustainability knowledge was not substantially higher than the Spring 2012 cohort.

Table 6.2. Analysis of sustainability concept maps generated by capstone design students using holistic scoring method [mean (standard deviation)].

	Fall 2011	Spring 2012	Combined	ANOVA	
	(n = 51)	(n = 93)	(n = 144)	$F(1, 142)$	p
Comprehensiveness	1.4 (0.5)	1.2 (0.5)	1.3 (0.5)	4.33	0.039*[1]
Organization	1.3 (0.6)	1.3 (0.5)	1.3 (0.5)	0.024	0.877
Correctness	2.9 (0.4)	2.9 (0.4)	2.9 (0.4)	0.264	0.608
Total	5.6 (0.9)	5.4 (0.8)	5.4 (0.8)	2.37	0.126

[1]Levene's test for equality of variances was violated [$F(1, 142) = 7.16$, $p = 0.008$]. Relationship still significant according to Welch's test [$F(1, 99.19) = 4.22$, $p = 0.043$].

<u>Categorical Approach</u>

The categorical scoring method was used to supplement analysis provided by the traditional and holistic approaches. The student-level complexity index (CO_j), which indicates overall quality of sustainability knowledge, and the number of inter-links (NIL), which are connections between concepts from different categories, were similar for both cohorts (CO_j = 10.4; NIL = 6.6) (Table 6.3). Category relevancies (Figure 6.1) between cohorts were also similar, with natural resources (24.3%) and the environment (26.5%) being the categories most included in student cmaps, and spatial imbalances (0.13%) and education (0.95%) being among the least incorporated categories.

Table 6.3. Mean categorical scores for sustainability cmaps created by capstone design students [mean (standard deviation)].

	Fall 2011	Spring 2012	Combined	ANOVA	
	(n = 51)	(n = 93)	(n = 144)	F(1, 142)	p
Number of Inter-Links	6.1 (4.4)	6.9 (4.9)	6.6 (4.7)	0.781	0.378
Complexity Index (CO_j)	9.8 (12.0)	10.8 (12.0)	10.4 (12.0)	0.231	0.631

[1]Some variables in this table exhibit kurtosis/SE > 3.29. However, since no significant relationships were found, rate of Type I error not relevant. Relationships still not significant when using nonparametric Kruskal-Wallis test.

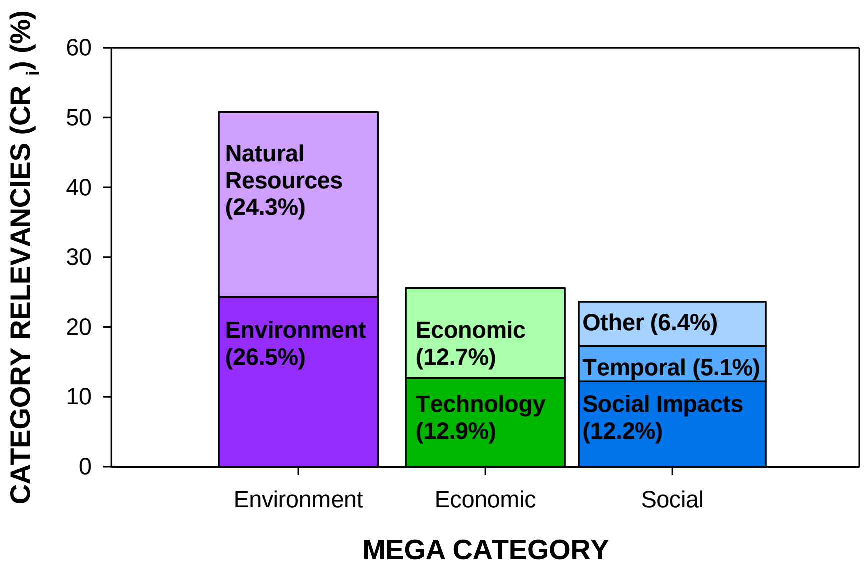

Figure 6.1. Category relevancies (CR_i) for sustainability cmaps created by capstone design students (n = 144) ("Other" represents stakeholders, values, education, and spatial imbalances).

Demographic Effects

Few differences in cmap scores, regardless of scoring approach, were found based on demographics. Civil engineers emphasized the economic mega-category (M = 28.7%, SD = 19.0%) significantly more than environmental engineers (M= 17.7%, SD = 11.7%) [$F(1, 135) = 8.71$, $p = 0.004$], while domestic students emphasized the economic mega-category (M = 28.0%, SD = 18.9%) more than international students (M = 17.2%, SD = 11.0%) [$F(1, 134) = 6.40$, $p = 0.013$]. No differences in cmaps were found based on gender.

Discussion

Comparing Concept Map Scores and Student Perceptions

General Conceptual Understanding

Both student perceptions and cmap scores suggest overall student sustainability knowledge to be somewhat limited. Specifically, slightly less than half of students were "extremely" confident in their abilities to discuss the overall concept of sustainable development (Table 4.2). It is common for student perceptions to reveal deficiencies in sustainability knowledge [132, 133, 135, 136], including a study by Kagawa that revealed only one-third of University of Plymouth students (n = 1889) to be "very familiar" with sustainable development. Similarly, cmap scores for Georgia Tech CEE students also showed evidence of insufficient sustainability knowledge (Tables 6.1-6.3). Specifically, the mean total holistic score for student-generated cmaps was only 5.4 out of 9.0, which is similar to the mean for a group of students reported to have recently completed a green engineering course (M = 5.1) [151]. In addition, the complexity index for CEE students (CO_{cohort} = 10.4) was much lower than for a group of 19 sustainability experts (CO_{cohort} = 24.8), but within the range shown for a large group of European undergraduates (CO_{cohort} = 0.5 – 26.9) [197]. Overall, improvements in sustainability knowledge are needed for

CEE students to become as proficient as sustainability experts and other top-performing undergraduates.

Breadth and Depth of Knowledge

Both assessment methods supported the need to improve the depth and breadth of student knowledge. The holistic approach showed that the mean comprehensivenes sub-score, which encompases both breadth and depth of student knowledge, was especially low (1.3 on a three-point scale) (Table 6.2). Similarly, the mean number of concepts (an indicator of knowledge breadth) was only 13.4 for CEE undergraduates (Table 6.1), as compared to 19.8 for sustainability experts and 16.9 for UK students having completed a variety of sustainability-related courses [117, 197]. Survey results concur, given that only approximately one-third of students were “extremely” confident in their abilities to discuss economic, environmental, or social aspects of sustainability (Table 4.2). Indeed, there is potential to further broaden and deepen student sustainability knowledge.

Balance of Knowledge

Survey results and cmap scores differ somwhat in their assessment of the balance of student knowledge among the three sustainability dimensions. Despite the overall low confidence in sustainability knowledge, students’ percieved their understanding to be relatively balanced among the three sustainability dimensions (M = 4.9 out of 7.0 and $\pi_{6\text{-}7}$ was approximately 30% for each dimension) (Table 4.2). Conversely, category relevancies suggest that student cmaps over-emphasized environmental concepts, as compared to economic and social concepts (Figure 6.1). Similarly, cmaps constructed by students from the UK also exhibited highest category relevencies for environmental and natural resources categories, while results of many student perceptions surveys also reinforce undergraduates’ emphasis on the environmental dimension [9, 134, 136]. Since promoting sustainability inherently requires an understanding and balancing of sustainability dimensions [22], educators should strive to ensure that students acquire a holistic perspective of sustainability.

Connectedness of Knowledge

In addition, both assessments agree that improvements to the connectedness of student knowledge networks are needed. In fact, few students expressed high confidence in their abilities to discuss the connections between sustainability dimensions (Table 4.2). Accordingly, cmaps only included less than seven inter-links (Table 6.3), as compared to almost 13 for a group of sustainability experts [197]. Since connectedness of knowledge increases one's ability to access concepts and is a key feature that differentiates expert and novice knowledge frameworks [138, 143], additional work is needed to aid CEE students in making connections between sustainability dimensions.

Knowledge Differences by Major

Although environmental engineering students were more confident in several aspects of their sustainability knowledge than civil engineering students (Table 4.6), cmap scores revealed no significant differences in conceptual understanding. For instance, a significantly higher proportion of environmental engineers, as compared to civil engineers, were extremely confident in their overall knowledge of sustainable development. However, no statistical differences were found between the total traditional, total holistic, or complexity indexes (CO_j) for the two groups. In addition, environmental engineering students were more confident in their knowledge of environmental sustainability than civil engineering students, although no significant differences were shown between the environmental mega-category distribution by major. Finally, environmental engineering students felt more confident in their abilities to discuss connections between sustainability dimensions than civil engineering students, although no statistical differences between the number of cross-links, the organization sub score, or the number of inter-links, were found between student groups. Like the current study, Bielefeldt [135] found environmental engineering students to be more confident in their knowledge of the term "sustainability" than civil engineering students. However, Bielefeldt [135] also reported that more environmental engineering students (86%) than civil engineering students (74%) were able to select the three sustainability pillars in a multiple-choice question. Perhaps no difference in sustainability knowledge by major was found in the current study because open-ended construction of cmaps may be more cognitively-challenging than answering one closed-ended question.

Insights for Designing Interventions to Improve Sustainability Education

Survey- and concept-map-based assessments provide several insights for improving sustainability education in CEE at Georgia Tech. First, both assessment methods support the need for efforts to improve sustainability knowledge. For instance, only about half of CEE seniors felt "extremely" confident in their abilities to discuss the overall concept of sustainability (Table 4.2), which was supported by complexity indexes being less than half of those for experts (Table 6.3). Second, although student knowledge is limited, the mean correctness sub-score of 2.9 on a three-point scale suggests that student knowledge is not plagued with inaccuracies (Table 6.2). As a result, interventions are needed to simply "enrich" student knowledge, which is considerably easier than correcting misconceptions [126, 127]. Finally, the assessments support specific qualities of student sustainability knowledge that need to be enriched. As discussed above, survey results and cmap scores suggest the need to guide students in developing sustainability knowledge that is balanced (in breadth and depth) and highly interconnected. Thus, student knowledge assessments suggest the need for, type of, and necessary outcomes of interventions to improve student understanding of sustainability.

Broad Implications for Selecting Sustainability Knowledge Assessments

Results of this study can broadly be applied to aid in selection and administration of sustainability knowledge assessments within many academic programs and institutions. The literature shows that administration of student surveys is the dominant method for analyzing student sustainability knowledge [9, 132, 134-136, 206, 230]. In the current study, both survey results and cmap score largely substantiated the limited nature of CEE student knowledge, which supports the use of simple student surveys to gauge overall sustainability understanding. However, one disadvantage of this approach is that students' perceptions of their cognitive understanding may be greater than their actual knowledge [212-214]. Indeed, environmental engineering students in the current study perceived themselves to be more knowledgeable about sustainability than their civil engineering counterparts (Table 4.6), even though no significant differences were detected in their cmaps. Given that cmaps have been shown to be valid for capturing student knowledge in a given domain [143], it is likely that environmental engineering students over-rated their sustainability knowledge. While student surveys may be simple and provide a rough assessment of student knowledge, more objective tools, such as cmaps, are suggested to supplement survey results to provide a more accurate and detailed view of student knowledge.

Limitations

Several limitations of this study are acknowledged. First, cmaps may not validly capture a student's complete understanding of sustainability. While lack of student motivation to construct cmaps that reflect their full knowledge may certainly compromise results, overall cognitive validity of cmaps for quantifying understanding of a given domain has been well-established [143, 150]. In addition, convergent validity was demonstrated for all three scoring methods (Tables 3.12-3.13). Second, cmap scores may be somewhat subjective since they are ultimately based on the perceptions of one or more expert judges. Threats on the reliability of cmap scores were minimized by using two expert judges that scored cmaps only after engaging in a process to calibrate their scoring criteria (See *Chapter Three* and Figure 3.6). Even for the most subjective holistic scoring approach, Krippendorff's alpha were within the range deemed acceptable for exploratory research. Thus, study methods were designed to promote validity and reliability of cmap scores.

Summary and Conclusions

An investigation was conducted to examine CEE students' conceptual understanding of sustainability. Seniors enrolled in 2011-2012 CEE capstone design courses at Georgia Tech completed a closed-ended survey to reflect on their sustainability knowledge (see *Chapter Four*), as well as a concept map to summarize their actual sustainability knowledge. Judges were employed to score the cmaps using traditional, holistic, and categorical approaches, and statistical analyses were used to analyze both cmap scores and survey results. The following conclusions were made based on the results.

1. Survey results and cmap scores largely concur that CEE students' overall sustainability knowledge is limited and displays little interconnectedness, which is an indicator of novice understanding.
2. Some discrepancies exist in assessment scores. Students perceived to equally understand the three sustainability dimensions, although most cmap concepts were environmentally-related.   Similarly, environmental engineers perceived to be more knowledgeable than civil engineers, although cmaps did not substantiate this claim.
3. Overall, survey and cmap scores verified the need for educational interventions to enrich CEE student knowledge to develop sustainability knowledge networks that are balanced (in breadth and depth) and interconnected.
4. While student surveys offer a relatively simple method for providing a rough assessment of student sustainability knowledge, more objective tools, such as cmaps, should be employed to provide a holistic and detailed assessment of student knowledge.

As the global landscape continues to evolve, engineers will be required to adapt their skills and professional practices to meet the needs of present and future generations. Already, engineers are increasingly called upon to develop and implement innovative solutions that serve a growing population, while simultaneously exploiting fewer resources and minimizing environmental impacts. As a result, it is imperative that engineering educators strive to equip their students with the knowledge necessary to act as sustainability-conscious engineers. Accurate sustainability knowledge assessments can aid in this endeavor by informing the design and evaluating the effectiveness of efforts to infuse sustainability content into undergraduate courses and curricula.

CHAPTER SEVEN

INVESTINGATING THE ABILITIES OF UNDERGRADUATES TO ENGAGE IN SUSTAINABLE DESIGN

Chapter Overview

The goal of this chapter is to examine the abilities of CEE students to apply sustainability knowledge during the design process (Research Question 1.4; Table 1.2). In addition to prompting seniors enrolled in CEE capstone design courses (Fall 2011 and Spring 2012) to reflect on their applied knowledge through completion of the Student Sustainability Survey (Table 3.19; See *Chapter Four* for results), capstone design reports completed between 2002 and 2011 were also analyzed using the Sustainable Design Rubric (see Figure 3.8 for research methods). Also, student projects sponsored by Forsyth County between 2004 and 2011, which focused on design of different sections of a multi-use trail, were examined as a unique case demonstrating relatively constant sponsor requirements over time and explicit sustainability demands. Survey and/or rubric results were used to address the following questions: (1) To what extent can students incorporate sustainability into the design process? (2) What are the impacts of sponsor expectations on student sustainable design performance? (3) Have student abilities to engage in sustainable design changed over time? Results will be used to describe implications for sustainability education in CEE at Georgia Tech, as well as broad application of the Sustainable Design Rubric.

Results

Survey-Based Assessment of Sustainable Design Abilities

Students were asked to reflect on their sustainable design abilities through completion of the Student Sustainability Survey (Table 4.3). Only approximately one-third of students felt “extremely confident” in their abilities to “develop sustainable solutions to engineering problems.” In addition, less than half of students indicated that they were “extremely confident” in their abilities to develop designs to meet specific sustainable design criteria, including “addressing community requests” and “minimizing natural resource depletion.” Overall, students perceived their sustainable design abilities to be fairly limited (See *Chapter Four* for additional details on survey results).

Assessment of Sustainable Design Abilities based on Examination of Capstone Reports

Overall Trends in Sustainable Design Scores (Fall 2002, 2006, 2011 Projects)

Capstone design projects generated by students during the Fall 2002 (n = 7), 2006 (n = 9), and 2011 (n = 14) semesters were analyzed using the Sustainable Design Rubric (Figure 3.8). Specifically, sustainable design expectations, student performance, and overall sustainable design indicators were examined.

Sustainable Design Expectations (Potential Points)

Potential points were computed and analyzed to capture the extent to which sustainable design criteria could reasonably have been applied in student projects, given instructor/sponsor requests and requirements (Figure 7.1; Table 7.1). The mean potential score for all 16 sustainable design criteria was 1.3 out of 3.0 points. In addition, 75, 18, and 7% of all potential scores were scored as 1’s, 2’s, and 3’s, respectively. Several trends were also noted for each of the four rubric dimensions.

CEE capstone design projects required students to mostly consider social aspects of sustainable design (Figure 7.1; Table 7.1). In fact, the mean potential score for all social criteria was 1.8 out of a possible 3.0 points. More specifically, as designated by the scoring convention, all projects required students to “protect human health and well-being” (M = 3.0). In addition, 25 out of 30 project sponsors required students to “address community and stakeholder requests" (*M* = 1.9) during the design process. Despite the emphasis on safety and incorporating stakeholders, few or no sponsors explicitly requested students to "consider local circumstances and cultures" or "use inherently safe materials."

Economic (*M* = 1.3), environmental (*M* = 1.2), and sustainable design tools (*M* = 1.1) considerations were emphasized less than the social dimension by project sponsors (Figure 7.1; Table 7.1). Related to economic sustainability, all students were required to "conduct a cost and/or cost-benefit analysis" (*M* = 2.0) as part of the course requirement. In the environmental dimension, 15 sponsors made requests that required students to "protect natural ecosystems" (*M* = 1.5), while 6 specified that students should "minimize natural resource depletion" (*M* = 1.2). For sustainable design tools, 7 sponsors suggested that students "incorporate systems analysis" (*M* = 1.2). Although to a limited extent, at least one criterion from each rubric dimension were reflected in sustainable design expectations.

Student Application of Sustainable Design Criteria (Earned Points)

Earned points were calculated to describe the extent to which students actually addressed sustainable design criteria, regardless of instructor/sponsor influence (Figure 7.1; Table 7.1). The mean earned score was 1.0 out of a maximum of 3.0 points. Overall, students considered criteria across all four rubric dimensions, with 51, 17, 21, and 11% of earned scores being 0's, 1's, 2's, and 3's, respectively.

During the design process, students emphasized social sustainability more than other dimensions (Figure 7.1; Table 7.1). Specifically, the mean earned score for all social criteria was 1.5. Nearly all groups "considered human health and well-being" (*M* = 2.7), while 26 groups also "addressed community and stakeholder requests" (*M* = 2.2). Only 10 groups "considered local circumstances and cultures" (*M* = 0.9). Nevertheless, social design criteria were most commonly incorporated into student projects and reports.

Table 7.1. Comparison between potential and earned scores for sustainable design criteria (n = 30 projects).

	Potential	Earned	Paired Samples *t*-Test	
	M (*SD*)	*M* (*SD*)	*t*(29)	*p*
Environmental Design Criteria				
Minimizes natural resource depletion	1.2 (0.4)	0.7 (0.9)	3.29	0.003**
Prevents waste	1.0 (0.2)	0.5 (0.7)	4.57	$\leq$ 0.001***
Protects natural ecosystems	1.5 (0.0)	1.7 (1.1)	-0.81	0.423
Uses renewable energy sources	1.0 (0.0)	0.1 (0.4)	14.00	$\leq$ 0.001***
Uses inherently safe materials (to environment)	1.0 (0.0)	0.2 (0.5)	9.90	$\leq$ 0.001***
Average for Environmental Design Criteria	1.2 (0.1)	0.6 (0.4)	8.26	$\leq$ 0.001***
Social Design Criteria				
Addresses community and stakeholder requests	1.9 (0.5)	2.2 (0.9)	-2.76	0.010**
Considers local circumstances and cultures	1.1 (0.3)	0.9 (0.9)	1.36	0.184
Protects human health and well-being	3.0 (0.0)	2.7 (0.6)	2.28	0.030*
Uses inherently safe and benign materials (to humans)	1.0(0.0)	0.1 (0.3)	20.15	$\leq$ 0.001***
Average for Social Design Criteria	1.8 (0.2)	1.5 (0.4)	4.16	$\leq$ 0.001***
Use of Sustainable Design Tools				
Incorporates life cycle analysis	1.0 (0.0)	0.4 (0.6)	6.24	$\leq$ 0.001***
Incorporates environmental impact assessment tools	1.1 (0.3)	0.3 (0.6)	6.71	$\leq$ 0.001***
Incorporates systems analysis	1.2 (0.4)	1.3 (0.8)	-0.72	0.476
Uses innovative technologies to achieve sustainability	1.1 (0.3)	0.7 (0.9)	2.56	0.016*
Average for Sustainable Design Tools Criteria	1.1 (0.1)	0.7 (0.4)	5.74	$\leq$ 0.001***
Economic Design Criteria				
Considers economic impacts of environmental criteria	1.0 (0.3)	0.8 (1.0)	1.03	0.312
Considers economic impacts of social design criteria	1.0 (0.0)	0.7 (0.9)	1.87	0.071
Conducts a cost and/or cost-benefit analysis	2.0 (0.0)	1.4 (0.9)	0.32	$\leq$ 0.001***
Average for Economic Design Criteria	1.3 (0.1)	1.0 (0.5)	3.53	$\leq$ 0.001***
Average for all Design Criteria	1.3 (0.1)	0.9 (0.3)	8.12	$\leq$ 0.001***

*$p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$

Economic (M = 1.0), environmental (M = 0.6), and sustainable design tools (M = 0.7) considerations were addressed in student reports less than the social dimension (Figure 7.1; Table 7.1). Related to economic sustainability, 26 groups "conducted a cost and/or cost benefit analysis" (M = 1.4), due to course requirements. In the environmental dimension, 23 groups showed evidence of "protecting natural ecosystems" (M = 1.7), while 14 teams "minimized natural resource depletion" (M = 0.7). For sustainable design tools, 24 groups "incorporated systems analysis" (M = 1.3). Although social sustainability was highly reflected in reports, other dimensions were also considered.

Comparing Project Potential and Student Actions (Potential versus Earned Points)

Sustainable design scores indicated that students could have reasonably further incorporated sustainability into their projects (Figure 7.1; Table 7.1). Specifically, the mean sustainable design index was 0.41 on a scale from -3.0 to 3.0 (Figure 3.9), suggesting that students "met the expectations" of their project sponsors and course instructors (Figure 7.2A). When comparing the averages for all design criteria, however, the mean earned score (M = 0.9) was still significantly lower ($p \leq 0.001$) than the mean potential score (M = 1.3). As a result, students had opportunities to improve the sustainability of their designs.

Earned means were statistically ($p \leq 0.05$) lower than potential means for 10 of the 16 criteria across all four of the rubric categories (Figure 7.1; Table 7.1). Among those criteria with the greatest deficiencies in the environmental category were "uses renewable energy sources" and "uses inherently safe materials (for environment)." Similarly, a large difference between potential and earned scores for "uses inherently safe materials (for humans)" was shown in the social dimension. Related to use of sustainable design tools and economic sustainability, deficiencies for "incorporates environmental impact assessment tools" and "conducts a cost and/or cost-benefit analysis" were also observed.

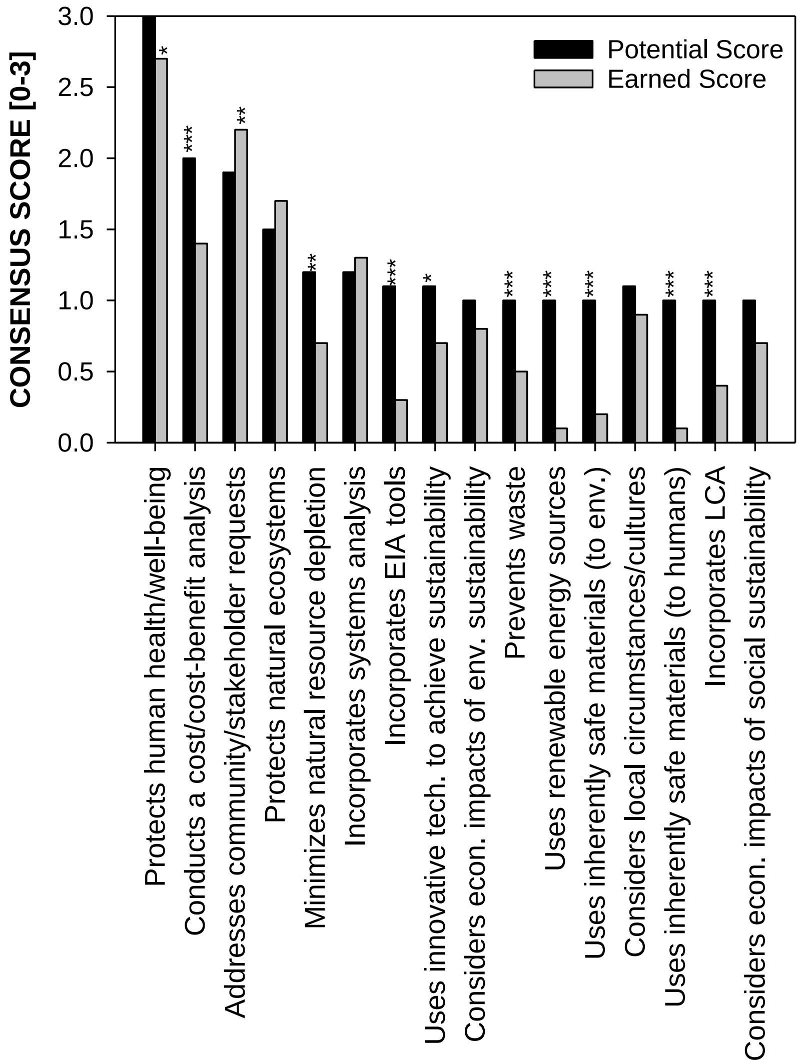

Figure 7.1. Mean consensus potential and earned scores for Fall 2002, 2006, and 2011 projects (*$p \leq 0.05$; **$p \leq 0.01$, ***$p \leq 0.001$).

Students met or exceeded sustainable design expectations for some criteria. Notably, no statistical differences between potential and earned scores were demonstrated for "protects natural ecosystems," "considers local circumstances and cultures," "incorporates systems analysis," and "considers economic impacts of environmental/social criteria" ($p \geq 0.05$). In addition, students exceeded expectations for "addresses community and stakeholder requests," since mean earned scores were significantly higher than mean potential scores ($p \leq 0.01$). Despite the many deficiencies in student reports, evidence of exceptional work related to some sustainable design criteria was demonstrated.

Historical Trends in Sustainable Design Scores

Capstone design projects completed by students between 2002 and 2011 were examined to identify any significant changes in sustainable design application, perhaps due to curricular improvements. In addition, student projects sponsored by Forsyth County focused on design of different sections of a multi-use trail were examined as a unique case. Students working on multi-use trail projects were subject to many of the same project specifications and constraints, since the sponsor and project location remained relatively constant. As a result, any changes in rubric scores could possibly be tied to increases in student design abilities

Potential Scores

Based on regression analyses, trends in potential scores did not change significantly over time (Tables 7.2-7.3) (Figure 7.2B). Specifically, variations in average potential scores, which ranged between 1.2 and 1.5 for projects developed between 2002 and 2011, were not significantly accounted for by differences in time ($p \geq 0.05$). Upon evaluating many multi-use trail project reports, judges agreed that the expectations of the Forsyth County representatives charged with guiding student projects did not change significantly over time. Due to this scoring convention, average potential scores for multi-use trail projects also remained constant between 2004 and 2011.

Earned Scores

Unlike potential scores, some differences in average earned scores, which capture the extent of student engagement in sustainable design, were observed over time (Table 7.2-7.3) (Figure 7.2C). In fact, time of project completion accounted for a significant ($p \leq 0.05$) amount of the variation among average earned scores for the criterion "considers economic impacts of environmental criteria" (Table 7.3). Interestingly, average earned scores for this economic criterion increased over time for all projects [$\beta = 0.16$, $t = 5.34$, $p = 0.028$], while they decreased for multi-use trail projects [$\beta = -0.682$, $t = -2.795$, $p = 0.021$]. Even so, mean earned scores for both general and multi-use trail did not vary substantially over time ($p \geq 0.05$).

Overall Sustainable Design Indexes

Trends in overall sustainable design indexes (Table 3.18) remained fairly constant over time (Figure 7.2A). Although the sustainable design indexes for projects completed during Fall 2002-2011 ranged between -0.1 and 0.9, the year in which projects were completed did not account for a significant amount of the variance in scores [$R^2 = 0.002$, $F(1, 28) = 0.06$, $p = 0.803$]. The maximum and minimum overall sustainable design indexes for multi-use trail projects were -0.2 and 0.6, respectively. Again, the year in which projects were completed did not explain a significant proportion of the variance in overall scores [$R^2 = 0.04$, $F(1, 9) = 0.36$, $p = 0.562$].

Table 7.2. Changes in potential and earned scores for Fall 2002, Fall 2006, and Fall 2011 projects over time (n = 30).

	Potential Points			Earned Points		
	R^2	$F(1, 28)$	p	R^2	$F(1, 28)$	p
Environmental Design Criteria						
Minimizes natural resource depletion	0.001	0.028	0.867	0.022	0.618	0.438
Prevents waste	0.005	0.142	0.710	0.001	0.026	0.873
Protects natural ecosystems	0.018	0.527	0.474	0.000	0.000	1.000
Uses renewable energy sources	-[1]	-	-	0.005	0.142	0.710
Uses inherently safe materials (to environment)	-	-	-	0.000	0.000	1.000
All Environmental Design Criteria	0.020	0.579	0.453	0.004	0.121	0.731
Social Design Criteria						
Addresses community and stakeholder requests	0.001	0.029	0.867	0.020	0.578	0.453
Considers local circumstances and cultures	0.062	1.843	0.185	0.067	2.017	0.167
Protects human health and well-being	-	-	-	0.004	0.104	0.750
Uses inherently safe and benign materials (to humans)	-	-	-	0.061	1.833	0.187
All Social Design Criteria	0.008	0.221	0.642	0.006	0.157	0.695
Use of Sustainable Design Tools						
Incorporates life cycle analysis	-	-	-	0.067	2.021	0.166
Incorporates environmental impact assessment tools	0.004	0.121	0.730	0.037	1.077	0.308
Incorporates systems analysis	0.001	0.019	0.892	0.006	0.166	0.687
Uses innovative technologies to achieve sustainability	0.004	0.121	0.730	0.020	0.563	0.459
All Sustainable Design Tools Criteria	0.002	0.045	0.834	0.014	0.395	0.535
Economic Design Criteria						
Considers economic impacts of environmental criteria	0.068	3.127	0.088	0.160	5.340	0.028*[2]
Considers economic impacts of social design criteria	-	-	-	0.061	1.816	0.189
Conducts a cost and/or cost-benefit analysis	-	-	-	0.203	7.123	0.013*[3]
All Economic Design Criteria	0.100	3.105	0.089	0.025	0.716	0.405
All Sustainable Design Criteria	0.005	0.151	0.700	0.004	0.122	0.729

[1]Earned score for this criterion remained constant.

[2](β = -0.400, t = -2.311, p = 0.028); [3](β = 0.450, t = 2.669, p = 0.013)

*$p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$

Table 7.3. Changes in potential and earned scores for multi-use trail projects completed between 2004 and 2011 over time (n = 11).

	Potential Points			Earned Points		
	R^2	$F(1, 9)$	p	R^2	$F(1, 9)$	p
Environmental Design Criteria	*Potential scores for trail projects remained constant, as per consensus scoring convention.*					
Minimizes natural resource depletion				0.183	2.015	0.189
Prevents waste				0.000	0.001	0.980
Protects natural ecosystems				0.058	0.550	0.477
Uses renewable energy sources				0.024	0.220	0.650
Uses inherently safe materials (to environment)				0.007	0.061	0.811
All Environmental Design Criteria				0.000	0.000	0.988
Social Design Criteria						
Addresses community and stakeholder requests				0.286	3.602	0.090
Considers local circumstances and cultures				0.005	0.045	0.837
Protects human health and well-being				-[1]	-	-
Uses inherently safe and benign materials (to humans)				-	-	-
All Social Design Criteria				0.124	1.279	0.287
Use of Sustainable Design Tools						
Incorporates life cycle analysis				0.094	0.933	0.359
Incorporates environmental impact assessment tools				0.093	0.924	0.362
Incorporates systems analysis				0.191	2.128	0.179
Uses innovative technologies to achieve sustainability				0.040	0.380	0.553
All Sustainable Design Tools Criteria				0.028	0.263	0.620
Economic Design Criteria						
Considers economic impacts of environmental criteria				0.465	7.810	0.021*[2]
Considers economic impacts of social design criteria				0.025	0.226	0.646
Conducts a cost and/or cost-benefit analysis				0.088	0.870	0.375
All Economic Design Criteria				0.369	5.268	0.047*[3]
All Sustainable Design Criteria				0.036	0.336	0.576

[1]Earned score for this criterion remained constant.
[2](β = -0.682, t = -2.795, p = 0.021); [3](β = -0.608, t = -2.295, p = 0.047)
*$p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$

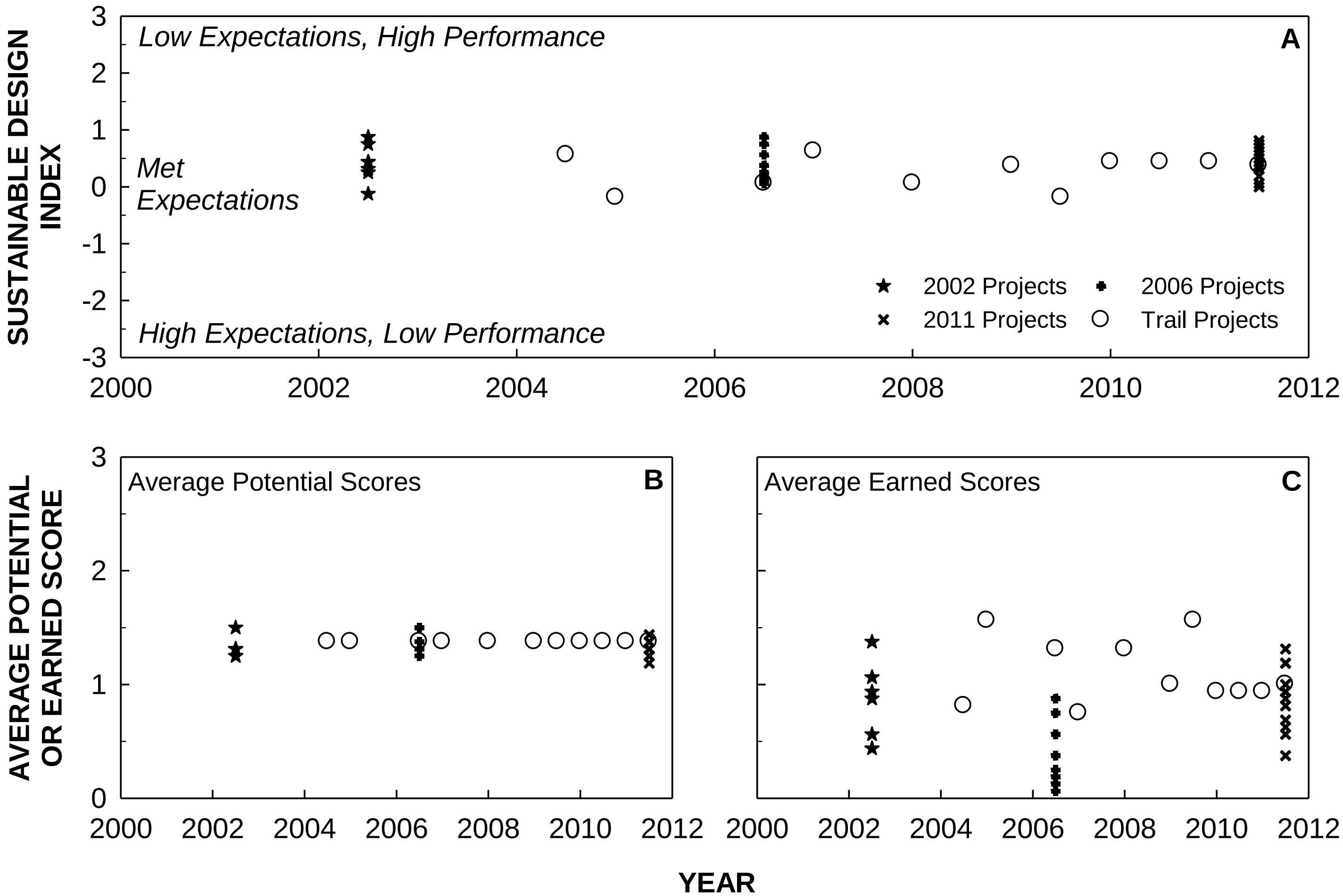

Figure 7.2. (A) Sustainable design indexes, (B) Average potential scores, and (C) Average earned scores for all general capstone design projects and multi-use trail projects.

Trends in Sustainable Design Scores by Project Type

Given that sustainable design indexes and sub-scores did not change substantially over time, analysis was conducted to compare mean scores for all Fall 2002, 2006, and 2011 projects with means for multi-use trail projects. In addition to the fact that project sponsor and constraints remained relatively constant, multi-use trail projects are also unique because promoting sustainability is an explicit project goal. As a result, multi-use projects represent a "best case scenario" for sustainable design potential of capstone design projects.

Potential Scores

Several differences in potential scores were identified between all capstone projects and those focused on multi-use trails. Specifically, expectations for "minimizing natural resource depletion" and "incorporating systems analysis" were significantly higher for multi-use trails as compared to projects in general ($p \geq 0.01$). Conversely, requirements for "protecting natural ecosystems" were statistically higher for all projects than for multi-use trail projects ($p \leq 0.01$). Nevertheless, average potential scores for all criteria were significantly higher for multi-use trails ($M = 1.4$) than for all projects ($M = 1.3$) ($p \leq 0.05$).

Earned Scores

Some aspects of sustainable design performance were greater for multi-use trail projects than for all capstone projects (Table 7.5). Perhaps due to the elevated expectations (Table 7.4), students completing multi-use trail designs demonstrated more significant efforts towards "minimizing natural resource depletion" than did students in general ($p \leq 0.01$). Although there was no evidence of Forsyth County requiring groups to go beyond simple cost estimation to "conduct cost-benefit analyses," students working on multi-use trails received higher earned scores for this criterion than their peers ($p \leq$

0.05). When examining mean earned scores for all criteria, however, no significant differences were demonstrated based on project type.

Overall Sustainable Design Indexes

Despite differences in environmentally-related sustainable design performance, overall sustainable design indexes (Table 3.18) were similar across project types. The mean sustainable design index for all Fall 2002, 2006, and 2011 projects ($M = 0.3$) was not statistically different than the mean for multi-use rail projects ($M = 0.4$) [$F(1, 39) = 1.93$, $p = 0.17$]. With means close to zero, students (on average) "met" overall sustainable design expectations (Figure 3.9).

Table 7.4. Comparison of potential scores for all projects (2002-2011) and multi-use trail projects (2004-2011).

	All Projects (n = 30)	Trail Projects (n = 11)	ANOVA	
	M (SD)	M (SD)	$F(1, 39)$	p
Environmental Design Criteria				
Minimizes natural resource depletion	1.2 (0.4)	2.0 (0.0)	41.85	$\leq$ 0.001***[1]
Prevents waste	1.0 (0.2)	1.0 (0.0)	0.361	0.552
Protects natural ecosystems	1.5 (0.6)	1.0 (0.0)	9.432	0.004**[1]
Uses renewable energy sources	1.0 (0.0)	1.0 (0.0)	-	-
Uses inherently safe materials (to environment)	1.0 (0.0)	1.0 (0.0)	-	-
Average for Environmental Design Criteria	1.2 (0.1)	1.2 (0.0)	1.112	0.298
Social Design Criteria				
Addresses community and stakeholder requests	1.9 (0.5)	2.0 (0.0)	0.177	0.676
Considers local circumstances and cultures	1.1 (0.3)	1.0 (0.0)	1.163	0.288
Protects human health and well-being	3.0 (0.0)	3.0 (0.0)	-	-
Uses inherently safe and benign materials (to humans)	1.0 (0.0)	1.0 (0.0)	-	-
Average for Social Design Criteria	1.8 (0.2)	1.8 (0.0)	0.027	0.871
Use of Sustainable Design Tools				
Incorporates life cycle analysis	1.0 (0.0)	1.0 (0.0)	-	-
Incorporates environmental impact assessment tools	1.1 (0.3)	1.0 (0.0)	0.747	0.393
Incorporates systems analysis	1.2 (0.4)	2.0 (0.0)	34.38	$\leq$ 0.001***[1]
Uses innovative technologies to achieve sustainability	1.1 (0.3)	1.0 (0.0)	0.747	0.393
Average for Sustainable Design Tools Criteria	1.1 (0.1)	1.3 (0.0)	14.042	$\leq$ 0.001***
Economic Design Criteria				
Considers economic impacts of environmental criteria	1.0 (0.3)	1.0 (0.0)	0.000	1.000
Considers economic impacts of social design criteria	1.0 (0.0)	1.0 (0.0)	-	-
Conducts a cost and/or cost-benefit analysis	2.0 (0.0)	2.0 (0.0)	-	-
Average for Economic Design Criteria	1.3 (0.1)	1.3 (0.0)	0.000	0.990
Average for all Design Criteria	1.3 (0.1)	1.4 (0.0)	6.665	0.014*,[2]

*$p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$; [1]Data fails Levene's test for homogeneity of variance. Welch's test cannot be performed because there is zero variance in potential points for trail projects, as per scoring convention. Chance of a Type I error low, since $p << 0.05$.

Table 7.5. Comparison of earned scores for all projects (2002-2011) and multi-use trail projects (2004-2011).

	All Projects (n = 30)	Trail Projects (n = 11)	ANOVA	
	M (SD)	M (SD)	F(1, 39)	p
Environmental Design Criteria				
Minimizes natural resource depletion	0.7 (0.9)	1.6 (0.7)	7.79	0.008**
Prevents waste	0.5 (0.7)	0.4 (0.7)	0.17	0.685
Protects natural ecosystems	1.7 (1.1)	2.2 (0.8)	1.97	0.168
Uses renewable energy sources	0.1 (0.4)	0.6 (0.9)	5.17	0.022[1]
Uses inherently safe materials (to environment)	0.2 (0.5)	0.1 (0.3)	0.26	0.617
Average for Environmental Design Criteria	0.6 (0.4)	0.9 (0.4)	5.10	0.030*
Social Design Criteria				
Addresses community and stakeholder requests	2.2 (0.9)	2.6 (0.7)	1.97	0.169
Considers local circumstances and cultures	0.9 (0.9)	0.4 (0.8)	3.09	0.087
Protects human health and well-being	2.7 (0.6)	3.0 (0.0)	1.88	0.178
Uses inherently safe and benign materials (to humans)	0.1 (0.3)	0.0 (0.0)	0.75	0.393
Average for Social Design Criteria	1.5 (0.4)	1.5 (0.3)	0.01	0.908
Use of Sustainable Design Tools				
Incorporates life cycle analysis	0.4 (0.6)	0.7 (0.8)	2.70	0.109
Incorporates environmental impact assessment tools	0.3 (0.6)	0.3 (0.6)	0.02	0.900
Incorporates systems analysis	1.3 (0.8)	1.8 (0.6)	3.04	0.089
Uses innovative technologies to achieve sustainability	0.7 (0.9)	0.6 (0.8)	0.15	0.704
Average for Sustainable Design Tools Criteria	0.7 (0.4)	0.8 (0.5)	1.28	0.265
Economic Design Criteria				
Considers economic impacts of environmental criteria	0.8 (1.0)	0.7 (0.9)	0.04	0.838
Considers economic impacts of social design criteria	0.7 (0.9)	0.8 (1.0)	0.14	0.713
Conducts a cost and/or cost-benefit analysis	1.4 (0.9)	2.0 (0.6)	3.97	0.053*,[2]
Average for Economic Design Criteria	1.0 (0.5)	1.2 (0.5)	3.37	0.074
Average for all Design Criteria	0.9 (0.3)	1.1 (0.3)	1.93	0.173

*$p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$; [1]Variance equality violated [$F(1, 39) = 26.80$, $p \leq 0.001$]. Relationship not significant as per Welch's test [$F(1, 11.140) = 2.736$, $p = 0.126$]; [2]Variance equality violated [$F(1, 39) = 5.25$, $p = 0.027$]. Relationship deemed significant as per Welch's test [$F(1, 24.254) = 5.271$, $p = 0.031$].

Discussion

Student Application of Sustainability Knowledge

Comparing Earned Scores with Student Perceptions of Sustainable Design Abilities

Both results of the Student Sustainability Survey (Table 4.3) and Sustainable Design Rubric (Figure 7.1) indicated that students are comfortable applying only a limited number of sustainability criteria during the capstone design process. Among the criteria with the five highest mean earned scores were "protects human health and well-being," "addresses community and stakeholder requests," "protects natural ecosystems," "conducts a cost and/or cost-benefit analysis," and "incorporates systems analysis." Similarly, student survey responses indicated that students are most confident in their abilities to "protect human health and well-being," "address community and stakeholder requests," and "protect natural ecosystems," as compared to other criteria.

On the other hand, results also highlighted criteria that students often do not consider during design. For instance, student confidence ratings (Table 4.3) and mean earned scores (Figure 7.1) were lowest for the criteria "use renewable resources," "incorporate environmental impact assessment tools," and "incorporate life cycle analysis." Although nearly half of students felt confident "using inherently safe and benign materials (Table 4.3)," the criteria "uses inherently safe and benign materials (for the environment and humans)" were among those with the lowest mean scores (Figure 7.1). Perhaps students assume that standard civil engineering materials (e.g. steel, timber, etc.) are indeed inherently safe; however, earned points were only awarded if students chose project materials based on environmental or health implications.

Comparing Earned Scores with Measures of Students' Conceptual Sustainability Knowledge

Several parallels were identified between students' conceptual understanding of sustainability and mean earned scores for capstone projects. First, in relation to overall knowledge quality, holistic cmap scores indicated students' conceptual knowledge to be deficient (Table 6.2), while low mean earned scores demonstrated relatively low application of sustainable design criteria during design (Table 7.1). Second, the breadth and depth of students' understanding was limited, as indicated by low comprehensiveness scores for cmaps (Table 6.2). Indeed, application of sustainability knowledge in capstone projects was also limited in breadth and depth with mean earned scores for 11 of the 16 criteria being less than 1.0, suggesting that they were seldom even "discussed" in reports (Table 7.1). Third, students were unlikely to "consider the economic impacts of environmental and/or social design criteria." Accordingly, cmaps with few cross-links (Table 6.1) indicated that students had difficulty drawing connections between concepts from different dimensions.

One discrepancy was identified between students' conceptual sustainability knowledge and demonstrated sustainable design abilities. While cmap results supported that students' sustainability knowledge networks were dominated by environmental concepts (Figure 6.1), groups most incorporated social design criteria into their capstone projects (Table 7.1). Perhaps, students do not recognize that issues of "protecting human health and well-being" and "addressing community and stakeholder requests," which they integrated well into their projects, are aspects of social sustainability. Nevertheless, in most cases, deficiencies in applied sustainability knowledge were accompanied with limitations in conceptual understanding.

Sustainable Design Expectations

In general, sustainable design expectations were quite low for capstone design projects. In fact, for projects completed during Fall 2002, 2004 and 2006, the mean potential score was only 1.3 out of a possible 3.0 points, indicating that criteria were "valid" but not required by the sponsors (Table 7.1). Nevertheless, all 16 criteria were still applicable to the capstone projects (Table 3.14).

Only a few criteria were generally specified by project sponsors (Table 7.1). Specifically "protect human health and well-being," "conduct a cost and/or cost-benefit analysis," "address community and stakeholder requests," and "protect natural ecosystems" received mean potential scores of 1.5 or greater, suggesting that multiple sponsors explicitly required consideration of these criteria. On the other hand, "use renewable energy sources," "use inherently safe materials (to environment and humans)," "incorporate life cycle analysis," and "consider economic impacts of environmental and social design criteria" all had average potential scores of 1.0, indicating that few or no sponsors explicitly required students to meet expectations. Overall, the mean potential score for the social sustainability rubric category was higher than any other dimension, indicating that sponsors most emphasized the social dimension of sustainability, which differs from stakeholders in higher education who often under-value the social dimension [118, 220, 230].

Comparing Student Performance and Sustainable Design Expectations

While the mean sustainable design indicator for Fall 2002, 2006, and 2011 projects suggests that sustainable design expectations were generally met (Figure 7.1), examining individual criteria reveals that students excelled in some aspects of sustainable design (Table 7.1). Namely, mean earned scores were either significantly higher than or not statistically lower than average potential scores for "addresses community and stakeholder requests," "protects natural ecosystems," "incorporates systems analysis," "considers local circumstances and cultures," and "considers economic impacts of social sustainability." As a result, students at least met or exceeded sustainable design potential for at least one criterion from each of the four rubric dimensions.

Despite the strengths of student projects, several aspects of sustainable design were largely unaddressed by students (Figure 7.1). In fact, mean earned scores were significantly lower than average potential scores for 10 of the 16 sustainable design criteria. Among those with the highest deficiencies were "conducts a cost and/or cost-benefit analysis," "incorporates environmental impact assessment tools," "prevents waste," "uses renewable energy sources," "uses inherently safe materials (to the environment and humans," and "incorporates life cycle analysis." Thus, even without alteration of capstone projects, there is much potential for seniors to further incorporate sustainability within their projects.

Interestingly, student performance was largely aligned with instructor and/or sponsor requests. First, many of criteria with the highest potential scores were also awarded the most earned points (Figure 7.1). In fact, "protects human health and well-being," "addresses community and stakeholder requests," and "protects natural ecosystems" were the only criteria with earned scores of at least 1.5; consequently, these criteria were among the few to also have potential scores of over 1.5. Conversely, those criteria with potential scores of 1.0, also received earned scores of less than 1.0. In addition, multi-use trail projects required to students to "minimize natural resource depletion" more than the average capstone project (Table 7.4); indeed, the mean earned score for this criterion was significantly higher for multi-use trail projects as compared to all capstone projects (Table 7.5). Although mean potential scores for "protects natural ecosystems" and "incorporates systems analysis" were also higher for multi-use trail projects (Table 7.4), there was no significant difference between average earned points based on project type (Table 7.5). Nevertheless, it is likely that increasing sustainable design expectations would prompt students to further incorporate sustainability into the design process.

Historical Trends in Sustainable Design Scores

Few trends in sustainable design scores were observed regardless of project type. Although potential scores for multi-use trail projects were not expected to change due to influence of the same project sponsor for each project, potential scores for general capstone projects completed during Fall 2002, 2006, and 2011 did not change significantly over time either (Table 7.2). However, the mean earned score for “considers economic impacts of environmental design criteria” statistically decreased over time for both general and multi-use trail projects (Tables 7.2-7.3). When considering all capstone projects, the mean earned score for “conduct a cost and/or cost-benefit analysis” significantly increased over time, indicating that students began to consider the economic impacts of multiple design alternatives and/or began to formulate cost-benefit analyses (Table 7.2). Given that potential scores did not change for this criterion, it is likely that the increase in earned scores is attributed to actual increases in student abilities.

Implications for Sustainability Education in CEE at Georgia Tech

Based on evaluation of student projects using the Sustainable Design Rubric, it is evident that efforts are needed to equip and encourage students to more extensively incorporate sustainability into the design process. In fact, evidence in student reports supported that application of nearly all 16 sustainable design criteria, with the exceptions of “addressing community and stakeholder requests” and “protects human health and well-being,” were less than “competent” (Table 3.16). While CEE instructors have sought to incorporate sustainability into their classes [181], efforts likely did not translate into improved student design capabilities, given that mean earned points were significantly lower than mean potential points for many sustainable design criteria (Figure 7.1).

Several strategies are suggested to improve student application of sustainability concepts during design. First, due to the shortcomings detailed above, new and innovative approaches, such as collaborative and experiential pedagogies supported by the work of Segalàs et al. [118], may be required to encourage student sustainability learning. Second, given that deficiencies in sustainable design abilities often coincided with similar limitations in conceptual understanding, novel strategies should focus on ensuring that students are equipped with fundamental sustainability knowledge before tackling sustainable design. Third, one mechanism for encouraging students to incorporate sustainability into the capstone design process may be to explicitly increase sustainable design expectations, since criteria receiving high earned scores also showed high potential scores. Overall, encouraging students to develop sustainable capstone designs requires application of novel strategies to ensure that students will be capable of engaging in sustainable design in their professional activities.

Broad Application of Sustainable Design Rubric

While the Sustainable Design Rubric was applied to capstone design projects from CEE at Georgia Tech, it can also be used by other departments and institutions. If utilized by other CEE departments, the rubric, including the 16 design criteria (Table 3.14), two rating scales (Table 3.16), and numerous examples (Table 3.15), may be directly applicable. While specific sustainable design examples may not be relevant for engineering programs beyond CEE, the design criteria and accompanying rating scales are still applicable to many engineering disciplines, since they are based on general sustainable design principles (Table 2.10) and related criteria (Table 3.14). In addition, the rubric is applicable for any design course, not solely capstone design. In fact, using the Sustainable Design Rubric to weave sustainability into multiple undergraduate design courses may facilitate horizontal integration, which could encourage students to incorporate sustainability into their professional designs and practices [102].

Limitations

Several limitations to these research methods are acknowledged. Foremost, when assigning potential and earned scores for each criterion, judges only had access to final student reports. As a result, an accurate evaluation of sponsor and/or instructor requests was achieved only if students made these requirements explicit in their reports. Indeed, students were often very clear, especially when defining their project objectives, concerning special instructions from sponsors. Similarly, when awarding earned points, judges could only give credit for consideration or application of those design criteria that were evident in the final report. However, just because a sustainable design element does not make it into the report does not mean that the group did not consider it. Nevertheless, the argument is made that the elements of research and analysis that the group deemed most important and spent the most time on would be evident in the final report. An additional limitation is related to the repeatability of judges' scores, due to the somewhat subjective nature of the rubric. For instance, depending on the context presented in the final report, some design activities could be classified as meeting different design criteria. As a result, an alternate set of judges evaluating the same set of projects may yield slightly different results. However, efforts were made to ensure the generation of reliable data, including training of judges and reporting of interrater reliability statistics. In addition, the extensive database of design examples for each criterion (Table 3.15) was developed to help aid in reproducibility of rubric application.

Summary and Conclusions

A sustainable design rubric, in combination with student survey responses, were used to examine CEE students' abilities to apply sustainability principles during design. All capstone design projects completed during Fall 2002, 2006, and 2011, as well as multi-use trail projects developed between Fall 2004 and 2011 were specifically analyzed to characterize both students' sustainable design performance and sustainability-related expectations of the projects themselves. The following conclusions were made based on the results.

1. While the 16 sustainable design criteria are fundamentally applicable to almost all CEE projects, instructor and/or sponsor requirements dictated that students most substantially "protect human health and well-being" and "conduct a cost and/or cost-benefit analysis."
2. Although student incorporation of sustainable design criteria was limited (11 criteria received earned scores of less than 1.0), students most extensively "protected human health and well-being" and "addressed community and stakeholder requests."
3. While students' conceptual understanding most reflected environmental sustainability, both sponsor requirements and student design activities most incorporated social design criteria.
4. In general, criteria that were most related to instructor and/or sponsor requirements were most extensively addressed by student groups.
5. Student abilities to engage in sustainable design have not substantially changed since 2002, which indicates that more innovative and aggressive measures to integrate sustainability into the CEE curriculum may be required.

Results from the evaluation of student projects suggest that efforts are needed to encourage students to incorporate a wider variety of sustainable design criteria into their capstone projects. Due to the influence of sponsor and instructor requests on student performance, it is suggested that sustainable design requirements be made explicit in the capstone design course. Broadly, the Sustainable Design Rubric can be used by other CEE and other engineering departments to quantify student sustainable design abilities in any design course. Given that engineers will be increasingly called upon to develop and implement innovative solutions that serve a growing population, while simultaneously exploiting fewer resources and minimizing environmental impacts, it is essential that undergraduate engineering education guide students in developing sustainable design skills. After all, the design decisions made by engineers have the potential to impact both current and future generations.

CHAPTER EIGHT

DEVELOPMENT OF A MODULE FOR TEACHING SUSTAINABILITY 'AROUND THE CYCLE'

Chapter Overview

The goal of this chapter is to present a sustainability module developed to enhance student sustainability knowledge (Research Question 2.1; Table 1.2). Based on literature reviews (see *Chapter Two*), as well as key findings about the current sustainability content of the CEE curriculum (see *Chapter Five*) and student sustainability knowledge (see *Chapters Six* and *Seven*), a series of active learning activities was designed (see *Chapter Three*, Figure 3.14 for methods) to guide students in sustainability learning. This module was implemented into CEE capstone and cornerstone design courses (see *Chapters Nine* and *Ten*) to examine its efficacy (see Appendices H and I for more details). The purpose of this chapter is to present the learning-cycle-based, structured-inquiry sustainability module, including its theoretical bases and incorporation of assessment procedures.

Summary of Assessment Results and Related Literature

Curricular Assessments

Several insights for improving CEE courses were gained from third-party and student-level assessments of the CEE curriculum using the STAUNCH® framework (Table 8.1). Foremost, student survey results revealed that the CEE curriculum is the primary means by which students learn about sustainability, which underscores the importance of curricular quality (Table 4.4). Furthermore, both assessment techniques indicated that there is potential for further incorporating sustainability into CEE classes, especially aspects of economic and social sustainability (Figure 5.1, Table 5.3). To aid in improvement of sustainability education, many students cited the need to provide guidance on incorporating sustainability into the design process, while few showed support for incorporating sustainability into existing courses (Table 4.5). Conversely, most experts agree that horizontal integration is essential for ensuring that students do not view sustainability as isolated from traditional engineering tasks [102]. Overall, curricular assessments show that although the CEE curriculum does expose students to sustainability, additional efforts are needed to aid students in developing not only a more sophisticated understanding of sustainability, but also more advanced sustainable design skills.

Knowledge Assessments

Like the curriculum itself, assessment efforts concurred that student sustainability knowledge is limited (Table 8.2). Student-generated cmaps and student survey results agree that while students certainly possess a basic conceptual understanding of sustainability, their knowledge is environmentally-focused without fully realizing the interconnectedness of all sustainability dimensions (Figure 6.1). Similar emphasis on the environmental dimension of sustainability has been demonstrated for many university stakeholders, including undergraduates [9, 118, 134, 136, 230].

Assessments also demonstrated potential for enhancing students' sustainable design skills. In fact, examination of student capstone projects using the Sustainable Design Rubric showed that most student groups do not consider sustainability during the design process, except when requirements are explicitly dictated by course instructors or external project sponsors (Figure 7.1; Table 7.1). Interestingly, however, students most met social design criteria when completing capstone projects (Table 7.1), despite the environmentally-related nature of their sustainability-focused cmaps (Figure 6.1). Perhaps this just underscores the need to integrate social sustainability concepts in CEE courses so that students understand that many of the design decisions made by civil and/or environmental engineers inherently impact social sustainability. Nevertheless, efforts to improve the depth, breadth, and connectedness of student knowledge are required to ultimately equip students to engage in sustainable design.

Characteristics of Intervention

Examination of student cmaps also provided an important perspective on the type of intervention that is needed to encourage enhancement of student sustainability knowledge. Other researchers propose that the nature of prior knowledge that students possess in a particular domain (either absent, incomplete, or incorrect) necessitates the type of learning that an instructor must facilitate (either knowledge addition, enrichment, or conceptual change) [126, 127]. While cmap scores in general highlighted the need to improve student knowledge, the correctness sub-score was quite high (2.9 out of a maximum of 3.0; Figure 6.1). As a result, students' prior knowledge related to sustainability was "incomplete," which requires efforts to "enrich" student knowledge [126, 127]. To "enrich" student knowledge, literature suggests that active and experiential pedagogies, in which students engage in and take responsibility of the learning process, are especially appropriate for promoting learning about sustainability [118]. Thus, interventions to improve student sustainability knowledge should guide students in building on their existing understanding to develop more comprehensive sustainability-related knowledge networks.

Table 8.1. Summary of results from assessments of the CEE curriculum at Georgia Tech.

	Student Sustainability Survey (*Chapter Four*)	Formal STAUNCH® Curriculum Assessment (*Chapter Five*)	Student Curriculum Assessment using STAUNCH® Framework (*Chapter Five*)
Content Breadth & Depth	N/A	Just over half of courses contained some type of sustainability content[1].	Few topics were rated as integrated into the curriculum "to a great extent" by students.
Content Balance	N/A	Curriculum emphasized environmental sustainability.	Curriculum emphasized environmental and cross-cutting topics.
Content Connectedness	N/A	Cross-cutting topics[2] were the second most common sustainability topics covered in courses.	Many cross-cutting topics[2] were viewed as integrated into the curriculum "to a great extent."
Role of CEE Curriculum	CEE courses were the primary means for student learning about sustainability.	N/A	N/A
Overall Quality of Curriculum	Room for improvement with only 13% of students indicating sustainability education quality to be "excellent."	Room for improvement with the contribution metrics being in the "medium" range.	N/A
Strategies for Course/ Curriculum Reform	Providing more guidance on applying sustainability during design suggested by over half of students.	N/A	N/A

[1]Overall strength metric was "medium."
[2]Cross-cutting topics often require integration of economic, environmental, and social sustainability knowledge.

Table 8.2. Summary of results from assessments of student sustainability knowledge.

	Student Sustainability Survey (*Chapter Four*)	Concept Maps (*Chapter Six*)	Sustainable Design Rubric (*Chapter Seven*)
Knowledge Breadth & Depth	Only about one-third of students were confident in their abilities to discuss more specific dimensional aspects of sustainability.	With a mean comprehensiveness[1] sub-score of just over 1.0 on a 3.0-point scale, breadth and depth of knowledge were limited.	Mean earned scores for most criteria were less than 1.0, as they were seldom even “discussed” in reports.
Knowledge Balance	Students perceived knowledge of three dimensions to be low, but balanced.	Cmaps contained predominately environmental concepts.	Highest earned scores were demonstrated for social design criteria.
Knowledge Connectedness	Only about one-third of students were confident in their abilities to discuss connections between sustainability dimensions.	Student cmaps, on average, contained fewer connections between concepts from different categories (inter-links) than expert cmaps[2].	Student abilities to consider economic impacts of meeting environmental and/or social design criteria were limited (earned scores less than 1.0).
Overall Quality of Conceptual Knowledge	Knowledge somewhat limited with less than half of students being “extremely” confident in abilities to discuss sustainable development.	Overall cmap scores showed that students have some understanding of sustainability, but that improvements in knowledge are needed.	N/A
Overall Ability to Apply Knowledge	Only about one-third of students were very confident in their abilities to develop sustainable solutions to engineering problems.	N/A	Student application of sustainability in capstone projects was limited, while often still meeting sponsor requirements.

[1]Results for traditional and categorical cmap scoring methods were similar.
[2]Results for traditional and holistic scoring methods were similar.

Module Goals and Objectives

A sustainability module was designed to address shortcomings of the CEE curriculum and student knowledge (Tables 8.1-8.2). The ultimate goal of this module was to guide undergraduate CEE students in learning about and applying sustainability concepts during design. Originally, the module was developed for incorporation into Capstone Design; however, feedback from participating seniors was used to create a slightly altered version for implementation in Civil Engineering Systems (CEE cornerstone design course). Capstone and cornerstone versions of the module were very similar, and even included identical learning objectives:

1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.
2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.
3. Analyze the impacts of a project on the economic, environmental, and social systems.
4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.

Module Components

The module was composed of five components that included material to promote student understanding of sustainable development and design (Figure 8.1). Students had opportunities to learn about sustainability concepts, examine how engineers consider sustainability during design, as well as practice some elements of sustainable design themselves. During the process, students also completed several assessments to track their learning.

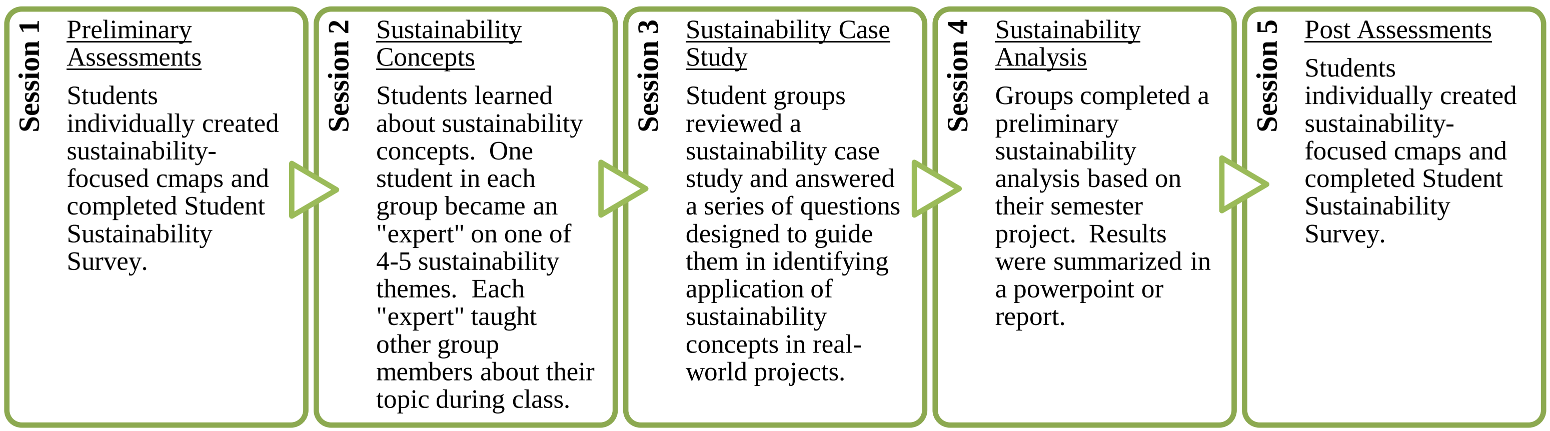

Figure 8.1. Five sustainability module components.

Session 1: Preliminary Assessments

At the beginning of the sustainability module, students were asked to reflect on their prior sustainability knowledge. First, students completed the Student Sustainability Survey (Appendix C), which prompted them to indicate their interest in, prior knowledge of, and educational experiences related to sustainability. Next, students engaged in a concept mapping workshop, where they learned how to create cmaps using CmapTools. Afterward, students created cmaps on the focus question: "What is sustainability?" (Figure 3.6). Survey responses and student-generated cmaps were used to benchmark students' preliminary sustainability knowledge.

Session 2: Sustainability Concepts

The purpose of Session 2 was for students to collaboratively learn about sustainability concepts that could later be applied during their semester projects. Before class, capstone design students familiarized themselves with sustainable development by completing a series of activities independently: reading primary literature, responding to a reflection question, and reviewing a tutorial (Tables 8.4-8.3). Next, students in each group selected unique sustainability themes on which to become "experts." The themes included economic sustainability, environmental sustainability, social sustainability, sustainable engineering, and sustainability assessments (Table 8.3). Also before class, seniors read primary literature, responded to reflection questions, and reviewed tutorials to become "experts" on their sustainability themes (Tables 8.3-8.4). Using provided outlines, students prepared mini-lectures to guide group members in learning about their themes. Students also reviewed the tutorials for other sustainability themes. In class, students delivered mini-lectures while group members recorded key concepts using very structured outlines. Although each student became an "expert" on only one theme, in-class lectures ensured that group members learned about all sustainability themes.

Session 2 was conducted similarly for cornerstone design students, although some changes were made based on feedback from capstone design students (Figure 8.2). One of the primary concerns among seniors was that mini-lecture outlines, which were used both to plan talks and record key concepts during class, were too long and structured. As a result, students felt that there was insufficient time to engage in group discussions about sustainability themes (Table 9.7). Consequently, efforts were implemented to improve Session 2 for cornerstone design students. In one section of CEE 3000, students were still prompted to develop mini-lectures, but provided outlines were altered to be shorter and highlight only the most important concepts. Students were also directed to include a question-and-answer section at the end of their talks. In a second section of CEE 3000, students were instructed not to deliver a mini-lecture, but rather to prepare to lead a discussion with their group members based on reflection prompts (Table 8.4). To do this, students had to decide on the main points that needed to be addressed during discussions, as well as prepare to answer any questions from group members. As a result, implementations of Session 2 in cornerstone design were meant to allow students more flexibility to discuss sustainability themes, while still covering similar content as capstone design.

Table 8.3. Topics covered in tutorials[1] on sustainable development and sustainability themes.

Sustainable Development	Social Sustainability
• Tragedy of the Commons • Definition of sustainable development • Triple-Bottom-Line Model • Nested Dependencies Model	• Socially sustainable communities • Methods to promote social sustainability • Stakeholder engagement • Stakeholder mapping
Environmental Sustainability	Sustainable Engineering
• Fundamentals of ecosystems • Definition of environmental sustainability • Environmental impact assessments • Lifecycle analysis	• Sustainable design methodologies • Nine Principles of Sustainability Engineering • Strategic design tools (e.g. Design Abacus)
Economic Sustainability	Sustainability Assessment[2]
• Economic growth and development • Neoclassical and ecological economics • Five Capitals Model for economic sustainability	• Origin of sustainability assessments • EIA-driven sustainability assessment • Objectives-led sustainability assessment • Sustainability indicators

[1]Tutorials are 5-8 page documents that explain fundamental topics for each theme.
[2]Sustainability theme addressed only in capstone design course.

Table 8.4. Required readings and reflection questions for sustainable development and five sustainability themes.

Theme	Required Reading	Reflection Questions for Capstone Design	Reflection Questions for Cornerstone Design
Sustainable Development	[35][1]	Can humans escape the Tragedy of the Commons?	Can humans escape the Tragedy of the Commons?
Economic Sustainability	[6]	Why is economic development an important component of sustainable development?	Defend why you are a proponent of either weak or strong sustainability.
Environmental Sustainability	[234]	Why is environmental protection an important component of sustainable development?	Relate how the application of the precautionary principle may support environmental sustainability. You can also defend your opposition to the precautionary principle.
Social Sustainability	[235]	Why is social development an important component of sustainable development?	Recommend how engineers can promote the six characteristics of a socially sustainable community.
Sustainable Engineering	[13]	Why is it important for engineers to promote sustainable development?	Describe how the interrelations and tensions between the three sustainability dimensions can complicate sustainable design. How can adhering the 9 principles of sustainable design facilitate sustainable design?
Sustainability Assessments[2]	[236]	Why is sustainability assessment important to engineers?	Not applicable for cornerstone design.

[1]Sophomores given the option to watch online videos about sustainable development and the Tragedy of the Commons.
[2]Provided to seniors enrolled in capstone design who were divided into groups of five. Due to time restrictions and constraints of the semester project, CEE 3000 students were organized into groups of four.

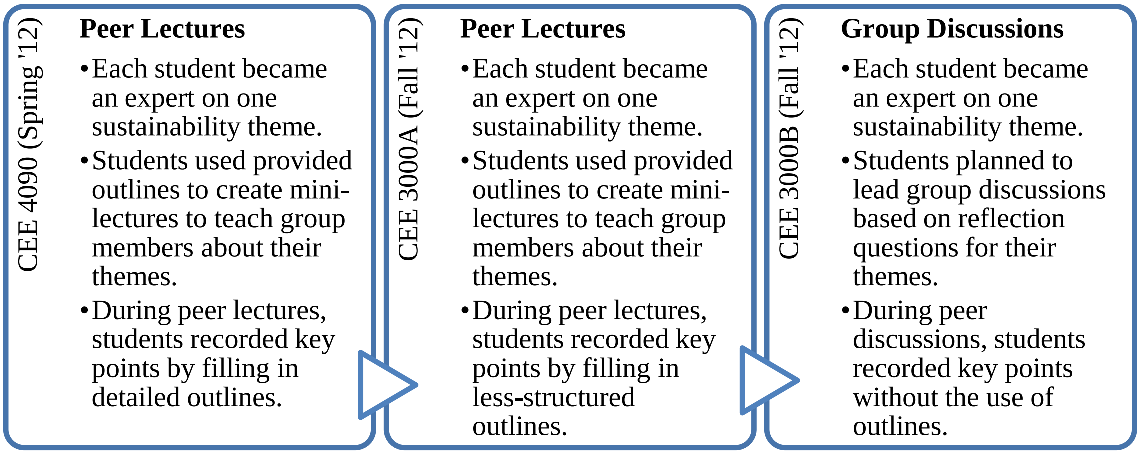

Figure 8.2. Comparison of Session 2 activities implemented in a Spring 2012 capstone design course and Fall 2012 cornerstone design courses.

Session 3: Sustainability Case Studies

The purpose of Session 3 was for students to identify application of sustainability concepts (learned during Session 2) in a sustainability case study. Before class, students read an extensive case study on the Beddington Zero Energy Development (BedZED) [237], a housing development in London that was designed to include numerous sustainability initiatives, such as use of only renewable energy, incorporation of low-impact materials, and promotion of waste recycling [237]. In class, students discussed the case study by answering a series of questions (Table 8.5) to aid them in examining how sustainability is addressed in real-world designs.

Case study questions were specifically tailored for capstone and cornerstone students. For seniors, questions were intended to help familiarize themselves with the creative thinking and innovative strategies that engineers can use to engage in sustainable design. While questions for cornerstone students were also meant to highlight the need for creativity during design, case study prompts were also designed and ordered to help students develop the ability to complete a systems analysis of an infrastructure system, which is one of the paramount goals of Civil Engineering Systems. Although case study questions differed somewhat between classes, they were commonly meant to allow students to practice sustainable design skills necessary for successful completion of the class in which they were enrolled.

Table 8.5. Questions used to guide students in identifying sustainability concepts in case studies.

BedZED Case Study Questions for Capstone Design Groups
1. What was the overall project goal?
2. What were the environmental, economic, and social objectives? What strategies were used to meet objectives?
3. Are the principles of sustainable design addressed in the BedZED project?
4. Explain why or why not the sustainability objectives outlined for the BedZED project were fulfilled.
BedZED Case Study Questions for Cornerstone Design Groups
1. What was the purpose of the BedZED project?
2. How do you think the engineers defined the boundaries of the BedZED project?
3. What are some of the components and functional characteristics of the BedZED project?
4. Identify economic, environmental, and social linkages for the BedZED project.
5. Describe the performance measures used for the BedZED project.
6. Are the principles of sustainable design addressed in the BedZED project.
7. Describe why or why not you believe the BedZED project is "sustainable."

Session 4: Preliminary Sustainability Analysis

The purpose of Session 4 was for students to apply sustainability concepts to their own semester projects (Tables 8.6-8.7). While capstone students were charged with completing an authentic engineering project, cornerstone students were prompted to complete a sustainability analysis of an existing infrastructure system (see *Chapter Three* for more details). First, all students completed a systems outline of their projects, including identification of economic, environmental, and social impacts of their projects. Students were also encouraged to complete a stakeholder analysis [238-240] to aid them in analyzing the social sustainability of their projects. Next, seniors were asked to identify strategies for meeting the 16 sustainable design criteria (Table 3.14) in the context of their projects, while cornerstone students were prompted to provide evidence on whether or not design engineers for their existing systems addressed each criterion. Seniors presented their work in powerpoint form, while cornerstone students produced a brief report.

Table 8.6. Requirements for preliminary sustainability analysis (capstone design).

System Description	Project Overview
• Provide a visual depiction of the system. • State the purpose of the system. • Define the boundary of the system. • List the components within the system. • Describe relationships between system components.	• State the main project goal. • Outline technical objectives. • State any constraints.
Sustainability Considerations	
• Potential Impacts: Outline potential positive and negative economic, environmental, and/or social impacts that could result from your project. • Stakeholder Analysis: Conduct a stakeholder analysis and display your results in a power/interest matrix. Identify any groups whose interests may need to be protected (high interest, low power). What methods would you use to promote stakeholder participation? • Sustainability Objectives: Based on the possible impacts previously outlined, propose objectives for each sustainability dimension. Provide at least one sustainability metric for each objective. • Sustainable Design Principles: Describe how three Principles can be applied to your project.	

Table 8.7. Requirements for preliminary sustainability analysis (cornerstone design).

Systems Perspective of Project	Adhere to sustainable engineering principles
• Provide a description, including objectives, for project. • Define system boundaries. • List important functional characteristics. • Outline potential economic, environmental, and social impacts.	• Analyze whether or not designers of system adhered to sustainable design criteria. • Provide metrics that could be used to determine whether or not sustainable design criteria were met.
Holistically Evaluate Design	
• Use design abacuses to depict how well sustainable design criteria were met. • Evaluate social sustainability of your project by completing a stakeholder analysis (optional). • Briefly evaluate the overall sustainability of your project.	

Module Workbook

Detailed workbooks were provided to both capstone and cornerstone students to aid them in module completion. Since the module was completed primarily by students with the instructor serving as only a facilitator, the workbook was essential for effective module delivery. Workbook contents for Session 2 included required readings, reflection questions, detailed tutorials, lecture outlines, and notes pages for all sustainability themes. Directed case study questions and project descriptions were included for Sessions 3 and 4, respectively. In addition, directions for completing before- and in-class assignments for each module component were included to ensure that students understood all requirements. See Appendices H and I for more information about module workbooks.

Module Theoretical Basis

Pedagogies Founded in Constructivist Theory

Design of the sustainability module reflects several instructional methods based on constructivist and social constructivist theories (Table 8.8). First, the module was designed to promote structured inquiry learning by requiring that students produce a sustainability analysis using information in the tutorials (Table 8.3), case studies (Table 8.5), and project instructions (Table 8.6). Second, collaborative learning was encouraged by requiring that students complete most activities and assignments in groups. Learning-by-teaching, a collaborative learning method, was employed as students prepared and delivered mini-lectures and/or discussions on assigned themes for their group members. Both inquiry-based and collaborative teaching methods promote active learning, which requires students to take responsibility for their own learning.

Pedagogies Founded in Experiential Learning Theory

Individual and group learning was facilitated by encouraging students to engage in Kolb's learning cycle (Table 8.8). Module content was developed to ensure that students completed each of the four phases of learning (Figure 8.3). Throughout the five-part module, students were introduced to primary literature, encouraged to reflect on a sustainability topic, provided with tutorials, and challenged to apply the new concepts to case studies and their semester projects.

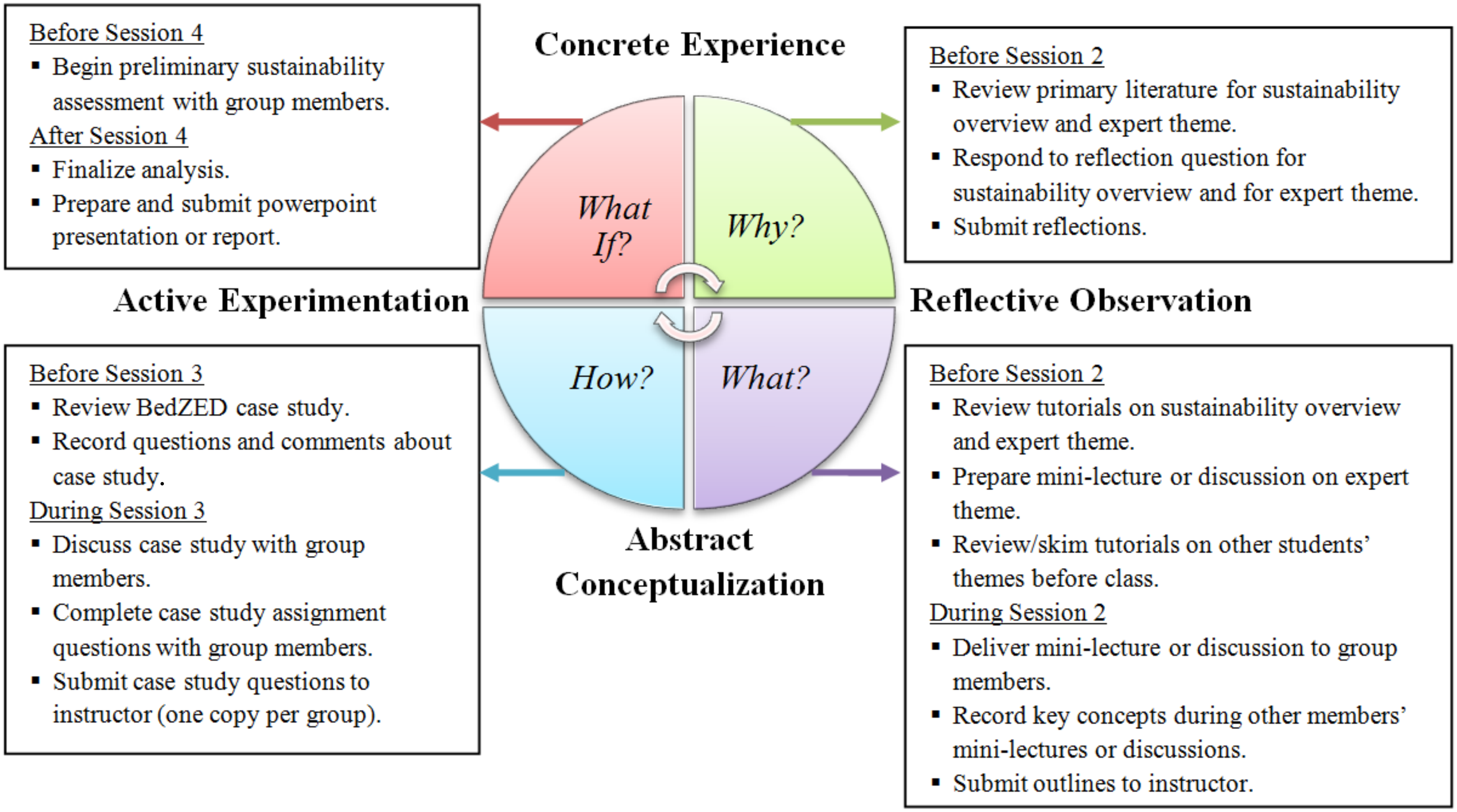

Figure 8.3. Sequence of module activities based on Kolb's learning cycle.

Table 8.8. Summary of pedagogies applied during module implementation.

Pedagogy	Theoretical Basis	Method of Application
Inquiry-based teaching and learning	Constructivism	• Students engaged in capstone or cornerstone design experiences. • Embedded module guided students in producing sustainability analyses for their semester projects.
Collaborative Learning	Social Constructivism	• Students worked in groups to learn module content and analyze a related case study. • Students worked in groups to complete their sustainability analyses. • Students prepared powerpoint presentations or reports within groups to summarize sustainability analyses to share with peers.
Learning-By-Teaching	Social Constructivism	• Students were responsible for becoming an expert on one sustainability theme. • Students were responsible for teaching group members about their themes.
Learning-Cycle-Based Instruction	Experiential Learning Theory	• Before class, each student was responsible for reading primary literature (CE) and responding to reflection questions (RO). • Before class, students reviewed their assigned themes and prepared mini-lectures or discussion plans (AC). • In class, students took notes about all themes (AC). • Students reviewed case studies and identified sustainability applications (AE). • Students applied concepts when preparing project sustainability analyses (AE).

Incorporation of Curricular and Knowledge Assessment Results

In addition to being designed based on constructivist and experiential learning theories, the sustainability module was developed using insights gained from student knowledge and curricular assessments (Table 8.9). To address limitations in students' conceptual understanding of sustainability, they were encouraged to develop a comprehensive (in breadth and depth), yet balanced, knowledge of sustainability through individual and group lectures/discussions on several sustainability themes. Student construction of cmaps, although included in Sessions 1 and 5 as assessment components, were also intended to provide students with opportunities to draw connections between sustainability dimensions, which are critical for developing expert-like knowledge [143].

Assessments also showed deficiencies in student sustainable design abilities (Table 8.9). To help students identify and address the economic, environmental, and social impacts of projects, they were prompted to examine the BedZED project as an exceptional example of sustainable design (Session 3). In addition, students were guided in completing their own sustainability analyses of their semester projects (Session 4). Overall, the module sought to aid students in developing a conceptual understanding of sustainability, as well as practice sustainable design skills.

Ultimately, the module was developed to address many of the aspects of sustainability that were deemed neglected in the CEE curriculum (Table 8.9). Specifically, in contrast to many CEE courses which emphasized environmental sustainability, module activities placed equal emphasis on the economic, environmental, and social dimensions of sustainability. Furthermore, presentation and application of sustainable design principles was intended to at least begin to address student desires to learn about the role of sustainability in the design process. In addition, the structure and content of the module was developed to be flexible enough to be integrated into any undergraduate CEE course with an existing design project. However, one sustainability module cannot be expected to transform an entire curriculum. Therefore, for meaningful reform to occur, implementation of the module must be supplemented with efforts to horizontally integrate sustainability into many courses.

Table 8.9. Summary of how sustainability module addresses limitations in student sustainability knowledge and sustainability content of the curriculum.

Knowledge/Curriculum Characteristic	Summary of Module Impact
Knowledge/Content Breadth & Depth	To improve knowledge breadth and depth, Session 2 of the module prompted students to learn about economic, environmental, and social sustainability through lectures and/or discussions with peers.
Knowledge/Content Balance	The three sustainability dimensions (economic, environmental, social) were equally represented in all module sessions.
Knowledge/Content Connectedness	Students created cmaps (Sessions 1 and 5) to help them explicitly demonstrate and analyze the inherently interconnected nature of sustainability.
Overall Quality of Conceptual Knowledge	Promoted improvement of students' overall conceptual knowledge by encouraging students to develop a balanced and connected understanding of sustainability.
Overall Ability to Apply Knowledge	After examining sustainable design through case study analysis (Session 3), students applied concepts themselves in the context of their semester projects (Session 4).
Strategies for Course/ Curricular Reform	The learning-cycle-based sustainability module encouraged active learning to promote not only learning about sustainability concepts, but also application of sustainability during design.
Role of CEE Curriculum	Since the CEE curriculum has a major impact on student sustainability learning, integrating the module into a required CEE course has the potential to positively impact student knowledge.
Overall Quality of Curriculum	Student participation in a five-part sustainability module may have only limited impacts if sustainability is not horizontally integrated into the curriculum.

Limitations

Several limitations of the sustainability module are acknowledged. First, unlike traditional engineering subjects (i.e. statics, dynamics, etc.), there is no accepted body of sustainability knowledge for undergraduate engineering students. As a result, some may find the content of the module to be incomplete. However, an extensive literature review on sustainability and sustainable design (See *Chapter Two*) was conducted, including examination of existing sustainability courses [101], to ensure appropriateness of module content. In addition, the module workbook was reviewed by a panel of faculty and graduate students from a variety of disciplines to ensure content validity (Figure 3.14). Even further, employment of learning-cycle- and inquiry-based teaching and learning approaches were intended to help students refine their own learning processes, in addition to improving their sustainability knowledge. Consequently, the module may help students develop the skills needed to acquire knowledge beyond what is included in the module itself. Second, while active learning pedagogies have been proposed to promote student learning [104, 118, 152], it has also been shown that students accustomed to instructor-centered classrooms may resist new and innovative teaching and learning methods [214]. Thus, while the module was designed to reflect theoretically-grounded pedagogies, efforts during implementation to win student acceptance may be required to ensure module success.

Summary and Conclusions

A sustainability module was developed to facilitate horizontal integration of sustainability into the CEE curriculum. The following points describe the purpose, components, and theoretical bases of the module.

1. The sustainability module was designed to guide students in learning about and applying sustainability concepts and principles in CEE courses.

2. The sustainability module was composed of five parts: administering preliminary assessments, encouraging students to learn about sustainability concepts and principles, providing students with a case study to demonstrate application of sustainability concepts and principles, prompting students to apply sustainability concepts and principles in a semester project, and administering post assessments.
3. Active learning and learning-cycle-based instruction, founded on social-constructivist and experiential learning theories, were applied in design of the sustainability module.
4. The module attempted to address some of the deficiencies in student knowledge and the CEE curriculum itself.

Though the proposed sustainability module cannot alone transform an undergraduate curriculum, it can be used to supplement other sustainability initiatives. Current undergraduate students will soon be responsible for local and global development projects that will impact both humans and the environment. Endorsing a sustainable development paradigm will require efforts to train engineering students, who will one day be responsible for the world's development projects, to engage in sustainable design.

CHAPTER NINE

IMPACTS OF IMPLEMENTING A LEARNING-CYCLE-BASED SUSTAINABILITY MODULE INTO A CEE CAPSTONE DESIGN COURSE

Chapter Overview

The goal of this chapter is to examine the impacts of implementing a learning-cycle- and inquiry-based sustainability module (See *Chapter Eight*) into a CEE capstone design course (Research Question 3.1; Table 1.2). Learning gains were compared for students enrolled in a traditional capstone design course (control cohort) and students enrolled in a capstone course modified to include the sustainability module (intervention cohort). Specifically, conceptual knowledge was assessed using concept maps (Figure 3.6) and items from the Student Sustainability Survey (Figure 3.10, Table 3.19). Sustainable design abilities were measured by applying the Sustainable Design Rubric to capstone project reports (Figure 3.8), as well as through administration of the Student Sustainability Survey. Students participating in the modified course were also asked to provide feedback on their experiences with the module through completion of the Module Evaluation Survey (Table 3.19). Results were used to address the following questions: (1) How does participation in the sustainability module impact students' understanding of sustainability? (2) To what extent does integration of the sustainability module into a capstone design course influence students' sustainable design abilities? (3) What insights do student feedback provide for future module implementations?

Results

An investigation was conducted to analyze the impacts of implementing a sustainability module into a CEE capstone design course on student learning. Several measures of students' conceptual sustainability knowledge and abilities to engage in sustainable design were compared between control and intervention cohorts. Feedback was also elicited from those students participating in the sustainability module.

Concept Map Scores

Students' conceptual understanding of sustainability was quantified by analyzing student-generated cmaps on the focus question: "What is sustainability?" Cmaps were scored using the traditional, holistic, and categorical methods to examine the content and structure of students' sustainability knowledge networks before and after completion of capstone design courses.

Traditional Method

Number of Concepts

Evaluation of pre- and post-cmaps using the traditional scoring method supports that students participating in the sustainability module experienced positive gains in the content of their sustainability knowledge (Table 9.1). Regardless of cohort, students included significantly more concepts in their cmaps at the end of the semester (M = 16.8) as compared to the beginning of the semester (M = 13.9) ($p \leq 0.001$). However, the increase in number of concepts was significantly higher for the intervention cohort ($\Delta_{post\text{-}pre} = 5.1$) as compared to the control cohort ($\Delta_{post\text{-}pre} = 0.9$) ($p = 0.09$). This suggests that participating in the sustainability module enabled students to improve the breadth of their sustainability knowledge.

Highest Hierarchy and Number of Cross-Links

In addition to enriching the content of sustainability knowledge, participation in the module also supported development of structurally complex sustainability knowledge networks (Table 9.1). Virtually no changes were observed in the highest hierarchy and number of cross-links between pre- and post-assessments for the control cohort. As a result, improvements in the highest hierarchy of cmaps was statistically higher for the intervention cohort ($\Delta_{post\text{-}pre} = +0.3$), as compared to the control cohort ($\Delta_{post\text{-}pre} = -0.3$) ($p = 0.009$). Similarly, improvements in the number of cross-links included in cmaps was substantially higher for the intervention cohort ($\Delta_{post\text{-}pre} = +1.5$), as compared to the control cohort ($\Delta_{post\text{-}pre} = -0.2$) ($p = 0.042$). This indicates that module participants were more able to develop the structural complexity of their sustainability knowledge, both in depth (indicated by highest hierarchy) and connectedness (indicated by number of cross-links), than those enrolled in the unmodified course.

Total Traditional Score

Overall, cmaps constructed by the intervention cohort were of a higher quality than those developed by students in the control cohort (Table 9.1). In fact, total scores generally increased from the beginning ($M = 54.6$) to the end ($M = 63.4$) of the semester, regardless of cohort [$F(1, 108) = 4.56$, $p = 0.035$]. However, the increase in total scores was significantly higher for students in the intervention cohort ($\Delta_{post\text{-}pre} = +20.2$), as compared to those in the control cohort ($\Delta_{post\text{-}pre} = -0.4$) ($p = 0.007$). As a result, students participating in the learning-cycle-based sustainability module were most able to enrich both the content and structure of their sustainability knowledge.

Holistic Method

Comprehensiveness

Analysis of pre- and post- cmaps using the holistic scoring approach also suggested that participation in the module improved the content and structure of student sustainability knowledge (Table 9.2). While comprehensiveness sub-scores significantly increased between pre- ($M = 1.33$) and post- ($M = 1.53$) assessments, regardless of cohort ($p \leq 0.001$), the magnitude of this increase was significantly higher for the intervention cohort ($\Delta_{post\text{-}pre} = +0.5$), as compared to the control cohort ($\Delta_{post\text{-}pre} = -0.1$) ($p \leq 0.001$).

As an indicator of student ability to adequately define and extensively understand a knowledge domain [131], comprehensiveness sub-scores suggest significant advancements in knowledge breadth and depth for students participating in the intervention.

Organization

In addition to comprehensiveness, the organization of student cmaps also improved after module completion (Table 9.2). Organization sub-scores generally increased between pre- (M = 1.30) and post-assessments (M = 1.55), regardless of cohort ($p \leq 0.001$). However, the magnitude of improvement was significantly higher for students participating in the module ($\Delta_{post\text{-}pre} = +0.5$) compared to those in the control cohort ($\Delta_{post\text{-}pre} = +0.0$) ($p \leq 0.001$). Since the organization sub-score captures students' abilities to properly arrange and connect concepts within cmaps, scores support that participation in the module led to more structurally advanced sustainability knowledge networks than participation in the capstone design course alone.

Correctness

While participation in the module positively impacted both the comprehensiveness and organization of sustainability knowledge, it had little effect on the correctness of sustainability knowledge (Table 9.2). Specifically, correctness sub-scores were generally close to 3.0 on a three-point scale and consequently did not vary significantly between pre- and post-assessments or between control and intervention cohorts ($p > 0.05$). Thus, student understanding was not naïve or filled with misconceptions. It is likely that capstone students, regardless of cohort, demonstrated correct sustainability knowledge because they were required to complete a sustainability-focused, sophomore-level course prior to enrollment in capstone design [179]. Furthermore, the correctness of student sustainability understanding is especially promising because the presence of misconceptions would require conceptual change, which can be especially difficult for instructors to facilitate [127, 128].

Total Holistic Score

Total holistic scores also confirmed the increase in overall quality of intervention cmaps (Table 9.2). Total holistic scores were significantly higher for post- (M = 6.0) than for pre-assessments (M = 5.6), regardless of cohort ($p \leq 0.001$). In addition, scores were statistically higher for the intervention (M = 6.0) than for the control cohort (M = 5.6), regardless of assessment (p = 0.016). However, the increase in scores between pre- and post-assessments were substantially higher for the intervention ($\Delta_{\text{post-pre}}$ = +0.9) than for the control ($\Delta_{\text{post-pre}}$ = -0.1) cohort ($p \leq 0.001$). Thus, improvements in comprehensiveness and organization of intervention cmaps led overall elevation of cmap quality.

Categorical Method

Category Distributions

Using the categorical method, it was determined that students in the intervention cohort developed a more balanced understanding of sustainability than their peers in the control cohort (Figure 9.1). Initially, both groups of students severely over-emphasized the environmental dimension, with approximately half of all concepts included in cmaps being related to the environment or natural resources. After their capstone design experiences, students in the control cohort still created environmentally-focused cmaps. Conversely, cmaps developed by students after participation in the sustainability module included concepts that nearly equally represented the environmental, economic, and social dimensions of sustainability. As a result, integration of the sustainability module into capstone design helps students develop a more holistic perspective of sustainability.

Table 9.1. Comparison between pre- and post-cmap scores determined using the traditional scoring approach for control and intervention cohorts [Mean (Standard Deviation)][1].

	Control Cohort (n = 38)		Intervention Cohort (n = 72)		Repeated Measures ANOVA $F(1, 108)$		
	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
NC	13.5 (6.2)	14.4 (8.5)	14.2 (6.2)	19.3 (10.3)	14.10***	3.89	7.06**
HH	3.5 (1.6)	3.2 (1.4)	3.3 (1.2)	3.6 (1.3)	0.06	0.08	7.04**
NCL	2.7 (2.7)	2.5 (3.4)	2.6 (3.2)	4.1 (6.6)	2.44	0.88	4.22*
Total	55.3 (25.9)	52.7 (36.0)	53.9 (32.3)	74.1 (63.1)	4.56*	1.59	7.65**

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

Table 9.2. Comparison between pre- and post-cmap scores determined using the holistic scoring approach for control and intervention cohorts [Mean (Standard Deviation)][1].

	Control Cohort (n = 38)		Intervention Cohort (n = 72)		Repeated Measures ANOVA $F(1, 108)$		
	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
Comp.	1.4 (0.5)	1.3 (0.5)	1.3 (0.5)	1.8 (0.7)	10.58**	3.60	24.86***
Org.	1.3 (0.6)	1.3 (0.5)	1.3 (0.5)	1.8 (0.8)	11.58***	2.68	11.58***
Corr.	3.0 (0.2)	2.9 (0.4)	2.9 (0.3)	3.0 (0.0)	1.37	0.08	3.60
Total	5.7 (0.8)	5.6 (0.8)	5.6 (0.8)	6.5 (1.0)	24.44***	5.99*	39.34***

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; [1]Comp and Org post fail Levene's test. Chance of Type I error small since $p << 0.05$ for significant relationships.

Complexity Indexes (CO_j)

In addition to improvements in the balance of student sustainability knowledge among dimensions, intervention cmaps also showed an improvement in overall complexity. The student-level complexity index (CO_j) increased between pre- (M = 11.3) and post-assessments (M = 21.0), regardless of cohort [$F(1, 108) = 9.48$, p = 0.003]. However, the increase in CO_j was substantially more for the intervention cohort ($\Delta_{post\text{-}pre}$ = 15.9) than the control cohort ($\Delta_{post\text{-}pre}$ = 3.4) [$F(1, 108) = 4.07$; $p = 0.046$]. As a result, students completing the sustainability module also showed the greatest improvements in category-based structural complexities.

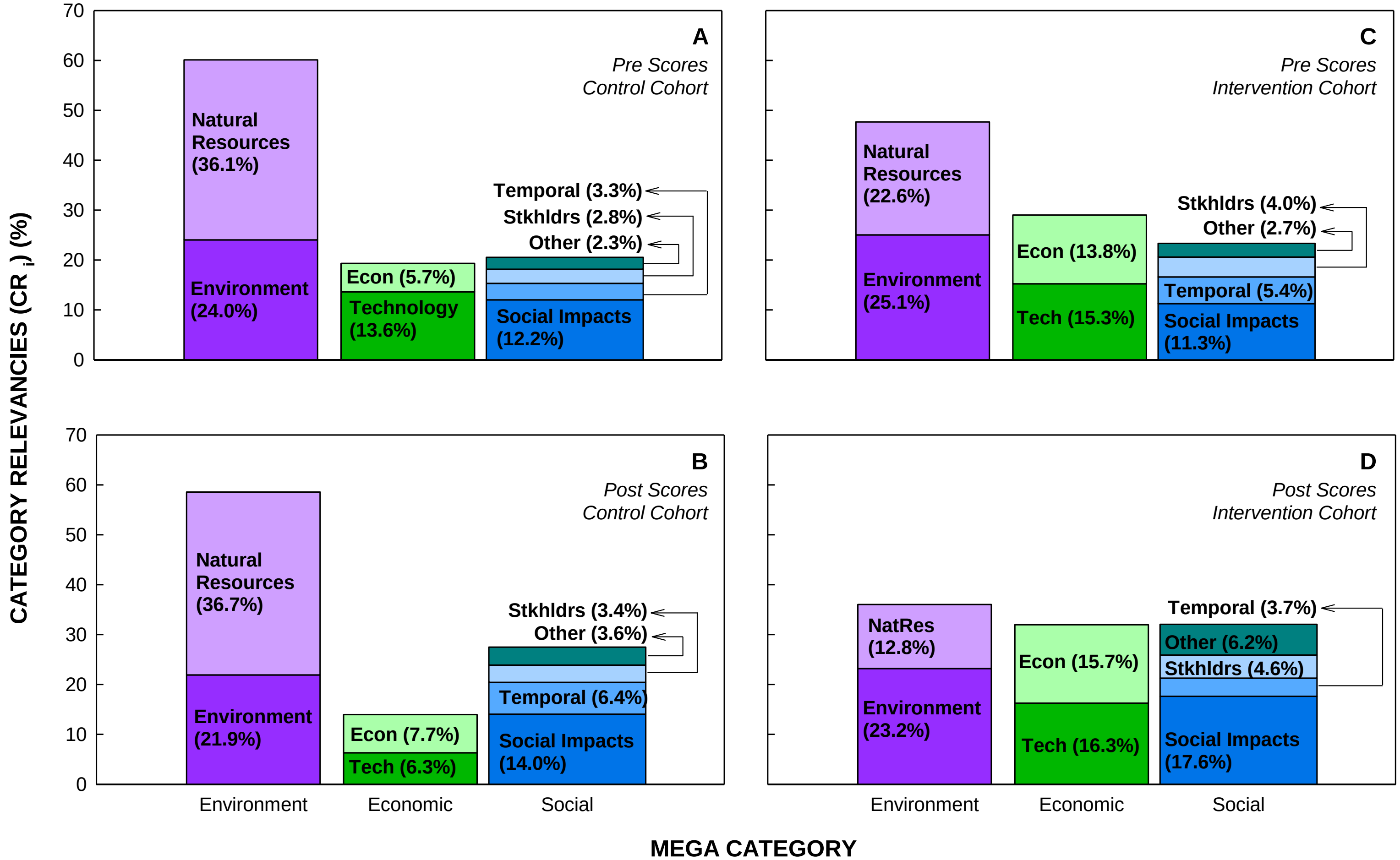

Figure 9.1. Comparison of (A) preliminary and (B) post category relevancies for students enrolled in a traditional capstone design course (control cohort), as well as (C) preliminary and (D) post category relevancies for students enrolled in a capstone course with an integrated sustainability module (intervention cohort) ("Other" represents values, spatial imbalances, and education categories).

Sustainable Design Scores

Student abilities to engage in sustainable design were examined by applying the Sustainable Design Rubric to student-generated capstone design projects. Specifically, sustainable design indexes, as well as potential and earned scores were compared between control and intervention cohorts.

Sustainable Design Indexes

Sustainable design indexes, which consider both student performance and sponsor expectations, were not impacted by participation in the sustainability module. In fact, no statistical differences between indexes were observed for students in the test cohort (M = 0.3, SD = 0.3) as compared to those in the control cohort (M = 0.4, SD = 0.2) [$F(1, 32)$ = 3.581, p = 0.068]. With a mean sustainable index close to zero on a scale of -3 to 3, all students essentially "met sponsor expectations" (Figure 3.9). Nevertheless, student engagement in module activities had no distinguishable impacts on overall application of sustainability concepts in their capstone design projects.

Potential Scores

Potential sub-scores, which capture sustainable design expectations, were similar for all projects. In fact, no statistical differences between potential scores for any of the 16 criteria were identified based on cohort (Table 9.3). Overall, the mean potential scores for each the control and intervention projects were 1.3 out of a maximum 3.0 points, indicating that sustainable design criteria were "valid" although not "required" by project sponsors (Table 3.16). As a result, student groups, regardless of cohort, could have met sustainable design criteria, even without encouragement from project sponsors.

Earned Scores

Unlike potential scores, earned scores differed slightly between cohorts (Table 9.4). For instance, the mean earned score for "minimizes natural resource depletion" was significantly higher ($p \leq 0.05$) for intervention projects ($M = 1.4$) as compared to control projects ($M = 0.6$). In addition, the mean earned score for "considers local circumstances and cultures" was also statistically greater ($p \leq 0.05$) for intervention projects ($M = 1.4$) than for control projects ($M = 0.6$). However, overall earned scores for all 16 criteria were approximately 1.0 for both cohorts, indicating that student sustainable design capabilities were still "developing" (Table 3.16). Even so, engagement in the sustainability module may have had positive influences on students' abilities to consider some aspects of environmental and social sustainability during design.

Table 9.3. Comparison between potential scores for design projects completed by students enrolled in a traditional capstone design course (control cohort, n = 14) and a capstone course with an integrated sustainability module (intervention cohort, n = 20).

	Control Cohort	Test Cohort	Combined	ANOVA	
	M (SD)	M (SD)	M (SD)	F(1, 32)	p
Environmental Design Criteria					
Minimizes natural resource depletion	1.2 (0.4)	1.2 (0.4)	1.2 (0.4)	0.010	0.922
Prevents waste	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	-[1]	-
Protects natural ecosystems	1.4 (0.5)	1.5 (0.6)	1.4 (0.6)	0.012	0.915
Uses renewable energy sources	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	-	-
Uses inherently safe materials (to env.)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	-	-
Average for environmental design criteria	1.1 (0.1)	1.1 (0.2)	1.1 (0.2)	0.001	0.979
Social Design Criteria					
Addresses community and stakeholder requests	1.9 (0.5)	2.0 (0.5)	2.0 (0.5)	0.194	0.663
Considers local circumstances and cultures	1.0 (0.0)	1.2 (0.4)	1.1 (0.3)	3.294	0.079
Protects human health and well-being	3.0 (0.0)	3.0 (0.0)	3.0 (0.0)	-	-
Uses inherently safe and benign materials (to humans)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	-	-
Average for social design criteria	1.7 (0.1)	1.8 (0.2)	1.8 (0.2)	1.601	0.215
Use of Sustainable Design Tools					
Incorporates life cycle analysis	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	-	-
Incorporates environmental impact assessment tools	1.1 (0.3)	1.1 (0.2)	1.1 (0.2)	0.064	0.801
Incorporates systems analysis	1.2 (0.4)	1.2 (0.4)	1.2 (0.4)	0.222	0.641
Uses innovative technologies to achieve sustainability	1.1 (0.3)	1.1 (0.3)	1.1 (0.3)	0.079	0.781
Average for sustainable design tools criteria	1.1 (0.1)	1.1 (0.1)	1.1 (0.1)	0.091	0.764
Economic Design Criteria					
Considers economic impacts of environmental criteria	1.1 (0.3)	1.0 (0.0)	1.0 (0.2)	1.448	0.238
Considers economic impacts of social design criteria	1.0 (0.0)	1.1 (0.2)	1.0 (0.2)	0.693	0.411
Conducts a cost and/or cost-benefit analysis	2.0 (0.0)	2.0 (0.0)	2.0 (0.0)	-	-
Average for economic design criteria	1.4 (0.1)	1.3 (0.1)	1.4 (0.1)	0.064	0.801
Average for all Sustainable Design Criteria	1.3 (0.1)	1.3 (0.1)	1.3 (0.1)	0.190	0.666

[1] No variations in means for Fall 2011 and Spring 2012 projects.

Table 9.4. Comparison between earned scores for design projects completed by students enrolled in a traditional capstone design course (control cohort, $n = 14$) and a capstone course with an integrated sustainability module (intervention cohort, $n = 20$).

	Fall 2011	Spring 2012	Combined	ANOVA	
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	$F(1, 32)$	*p*
Environmental Design Criteria					
Minimizes natural resource depletion	0.6 (0.9)	1.4 (1.1)	1.1 (1.1)	4.441	0.043*
Prevents waste	0.4 (0.6)	0.7 (1.0)	0.6 (0.9)	0.758	0.391
Protects natural ecosystems	1.6 (1.2)	1.8 (1.1)	1.7 (1.1)	0.204	0.655
Uses renewable energy sources	0.0 (0.0)	0.1 (0.3)	0.1 (0.2)	1.464	0.235
Uses inherently safe materials (to env.)	0.2 (0.6)	0.2 (0.5)	0.2 (0.5)	0.006	0.941
Average for Environmental Design Criteria	0.6 (0.3)	0.8 (0.6)	0.7 (0.5)	2.365	0.134
Social Design Criteria					
Addresses community and stakeholder requests	2.2 (0.9)	2.6 (0.5)	2.4 (0.7)	2.587	0.118
Considers local circumstances and cultures	0.6 (0.8)	1.4 (1.1)	1.1 (1.0)	4.149	0.050*
Protects human health and well-being	2.8 (0.4)	2.9 (0.7)	2.8 (0.6)	0.100	0.754
Uses inherently safe and benign materials (to humans)	0.0 (0.0)	0.10 (0.4)	0.1 (0.3)	0.693	0.411
Average for Social Design Criteria	1.4 (0.4)	1.7 (0.3)	1.6 (0.4)	7.305	0.011*
Sustainable Design Tools Design Criteria					
Incorporates life cycle analysis	0.5 (0.7)	0.4 (0.7)	0.4 (0.7)	0.184	0.671
Incorporates environmental impact assessment tools	0.4 (0.7)	0.5 (0.8)	0.4 (0.8)	0.266	0.610
Incorporates systems analysis	1.4 (1.0)	1.8 (0.7)	1.6 (0.9)	1.771	0.193
Uses innovative technologies to achieve sustainability	0.7 (1.0)	1.1 (1.3)	0.9 (1.2)	0.878	0.356
Average for Sustainable Design Tools Criteria	0.7 (0.5)	0.9 (0.6)	0.9 (0.6)	1.093	0.304
Economic Design Criteria					
Considers economic impacts of environmental criteria	0.4 (0.7)	0.5 (0.8)	0.4 (0.8)	0.266	0.610
Considers economic impacts of social design criteria	0.4 (0.9)	0.6 (0.9)	0.5 (0.9)	0.159	0.692
Conducts a cost and/or cost-benefit analysis	1.9 (0.7)	1.4 (0.6)	1.6 (0.7)	3.849	0.059
Average for Economic Design Criteria	0.9 (0.4)	0.8 (0.6)	0.8 (0.5)	0.139	0.712
Average for all Sustainable Design Criteria	0.9 (0.3)	1.1 (0.3)	1.0 (0.3)	3.397	0.075

*$p \leq 0.05$

Student Sustainability Survey

In addition to examining student generated cmaps and capstone design reports, items on the Student Sustainability Survey were used to gauge changes in students' perceptions of their sustainability knowledge. The percentages of students whose perceived conceptual understanding of sustainability were positively impacted by their capstone design experiences were similar for both the intervention and control cohorts (Table 9.5). Related to overall sustainable design capabilities, students' confidences to "develop sustainable solutions to engineering problems" or "evaluate a design based on sustainability criteria" were not significantly improved by participating in module activities (Table 9.5). However, those engaging in the module indicated heightened abilities to "address community and stakeholder requests," "incorporate life cycle analysis," and "use renewable energy sources," as compared to their peers in the control cohort (Table 9.6). Overall, based on student reflections of their own knowledge, the module primarily impacted abilities to apply select sustainable design criteria during design.

Table 9.5. Comparison between student-provided rankings to complete several tasks related to sustainable development (SD) before and after completion of a traditional capstone design course (control cohort) and a capstone course with an integrated sustainability module (intervention cohort).

Survey Prompt: The statements below are related to sustainable development. Indicate how confident you are in your ability to complete the listed tasks.	Control Cohort (n = 47, df = 1) [$\pi_{6\text{-}7}$] (%)			Intervention Cohort (n = 84, df = 1) [$\pi_{6\text{-}7}$] (%)			Positively Impacted Students[1] (%) (n = 131, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Control	Intervention	Pearson χ^2
Develop sustainable solutions to engr problems.	34.0	44.7	1.67	27.4	43.0	4.88*	21.3	41.7	0.394
Discuss the concept of SD.	48.9	61.7	2.00	45.2	61.6	5.53*	23.5	61.9	0.430
Discuss connections between poverty, population, consumption, and env degradation.	34.0	29.8	0.20	35.7	44.2	1.24	19.1	42.9	0.380
Discuss economic factors that affect SD.	29.8	36.2	0.60	34.5	38.4	0.40	19.1	38.1	0.022
Discuss environmental factors that affect SD.	27.7	42.6	3.77	36.9	44.2	0.86	21.3	42.9	0.110
Discuss social factors that affect SD.	23.4	51.1	7.35**	39.3	52.3	3.06	38.3	51.2	0.167
Evaluate a design based on sustainability criteria.	40.4	46.8	0.60	31.0	40.7	1.61	19.1	39.3	0.584

*$p \leq 0.05$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Table 9.6. Comparison between student-provided rankings to complete several tasks related to sustainable design before and after completion of a traditional capstone design course (control cohort) and a capstone course with an integrated sustainability module (intervention cohort).

Survey Prompt: The statements below are related to sustainable design. Indicate how important you think it is for engineers to be able to develop designs that meet the listed criteria. Also indicate how confident you are in your ability to develop designs that meet these criteria.	Control Cohort (n = 47, df = 1) [$\pi_{6\text{-}7}$] (%)			Intervention Cohort (n = 84, df = 1) [$\pi_{6\text{-}7}$] (%)			Positively Impacted Students[1] (%) (n = 131, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Cornerstone Cohorts	Capstone Cohort	Pearson χ^2
Addresses community and stakeholder requests	59.6	55.3	0.20	38.1	58.3	7.12**	19.1	35.7	3.96*
Considers local circumstances and cultures	55.3	46.8	0.80	36.9	52.4	4.67*	17.0	31.0	3.04
Incorporates life cycle analysis	36.2	40.4	0.29	23.8	52.4	17.65***	17.0	34.5	4.56*
Incorporates EIA tools	27.7	31.9	0.25	26.2	50.0	11.06***	19.1	36.9	3.46
Incorporates systems analysis	29.8	42.6	2.00	29.8	52.4	8.84**	25.5	31.0	1.77
Uses innovative technologies to achieve sustainability.	25.5	34.0	1.14	23.8	44.0	8.75**	19.1	44.0	2.15
Minimizes natural resource depletion	21.3	44.7	5.26*	34.5	69.0	19.34***	36.2	27.4	0.72
Prevents waste	27.7	42.6	3.27	36.9	51.2	4.60*	23.4	28.6	0.25
Protects natural ecosystems	44.7	53.2	0.67	39.3	53.6	4.34*	29.8	19.0	0.02
Protects human health and well-being	59.6	57.4	0.07	51.2	48.8	0.07	14.9	19.0	0.36
Uses inherently safe and benign materials	53.2	59.6	0.53	44.0	58.3	3.72	21.3	32.1	1.76
Uses renewable energy sources	40.4	42.6	0.07	29.8	53.6	11.06***	17.0	34.5	4.56*

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Student Feedback

To provide guidance in improving future module implementations, students in the intervention cohort were asked to critique the module. After some module sessions, students were encouraged to provide open-ended feedback, while they were prompted to complete the Module Evaluation Survey at the end of the semester.

After Module Sessions

Students in the intervention cohort provided feedback on their module experiences during reflection times at conclusions of Sessions 1 and 2 (Table 9.7). After Session 1, students indicated that although the activity ran relatively smoothly, more than the allotted time (3 hrs) would have been desirable for each group to complete student sustainability lectures on the five sustainability themes. During student talks, group members were required to record key concepts using instructor-provided outlines. While some students found it helpful to use the outlines as a guide, many felt that they restricted the group discussions. Student feedback after analyzing the BedZED case study during Session 3 was overwhelmingly positive. Many students indicated that examining a project dedicated to sustainability was helpful for extracting ideas that could be applied in their own projects. A limited number of students requested a case study that more closely aligned with their projects. While students provided constructive feedback, they suggested that the module activities ran fairly smoothly.

After Module Completion

At the end of the intervention course, students were provided with an opportunity to reflect on the module as a whole. Only 29.5% of students "strongly agreed" that the module helped them to learn about sustainability concepts, while even less (19.3%) indicated that the module helped them learn about sustainable design. Even still, only 15.9% of students "strongly agreed" that they enjoyed participating in the module. After examining open-ended student feedback (Table 9.7), it was found that students would have preferred to either (1) focus only on their capstone design projects, or (2) have module activities completed early in the semester. While a traditional capstone design course where students are expected to apply knowledge from all previous courses is certainly time-consuming and stressful, it is possible that the student feedback was especially negative because responses were collected a few days before final projects.

Table 9.7. Qualitative student feedback provided during and after the sustainability module.

Session 2 Reflections
• "[Session 2] went well, but the overall length was a little long."
• "[Session 2] went well. Our group shared lots of knowledge of each topic."
• "Session 2 went alright. [Completing lecture outlines] was a good way for us to better understand our teammates' topics."
• "Session 2 did go smoothly. However, the discussion was a bit too forced with the rigid structure of the worksheets."
Session 3 Reflections
• "Session 3 went very smoothly. It helped us all get on the same page and get our project going in a more sustainable direction."
• "Session 3 went really well. We discussed the BedZED project (disadvantages/advantages). With understanding how sustainable practices were implemented into their project, we could take away positive ideas/initiatives for our own capstone project."
• "Session 3 went well. It was interesting to learn about the BedZED project."
• "It is cool to learn about the BedZED project, but more variety would be nice."
Post-Module Reflections
• "Have all the assignments due during the first part of the semester because people might get busier [later]. Also, people might want to integrate the knowledge they gained during the module in their projects at an earlier stage"
• "I'm not really sure a module in the capstone design course is the best format…It seems everyone in the course is focused on their project and not on class activities in the module."
• "Perhaps [the module] would be best implemented before taking senior design."
• "Sustainable development within the capstone course is a good reminder of the concepts we need to know, but I believe that there should be less time dedicated to it during capstone."

Discussion

Impact of Module on Conceptual Sustainability Knowledge

Overall Improvements in Conceptual Knowledge and Brevity of Sustainability Module

The learning-cycle-based sustainability module likely had positive influences on student conceptual sustainability knowledge, despite the overall brevity of class time devoted to the module. According to analysis of student-generated cmaps, the content and complexity of students' sustainability knowledge networks were shown to improve significantly more ($p < 0.05$) between pre- and post-assessments for the intervention cohort than for the control cohort, regardless of the scoring method used to evaluate cmaps (Figure 9.2). Importantly, the structural complexity (measured by the highest hierarchy, number of cross-links, organization sub-score, and complexity index) increased statistically more for intervention students than for control students (Tables 9.1-9.2; Figure 9.1), which is a sign of knowledge integration rather than rote learning according to Besterfield-Sacre et al. [131]. Knowledge integration, in turn, is a key feature of expert semantic networks that improves the ability to access and utilize information [138]. Finally, while students' prior knowledge about sustainability was environmentally focused, as has been demonstrated for other undergraduates [9, 134], participation in the module facilitated development of a more balanced understanding among the three sustainability dimensions (Figure 9.1). Thus, results of all cmap scoring methods support that participation in the brief sustainability module promoted student development of more expert-like sustainability knowledge.

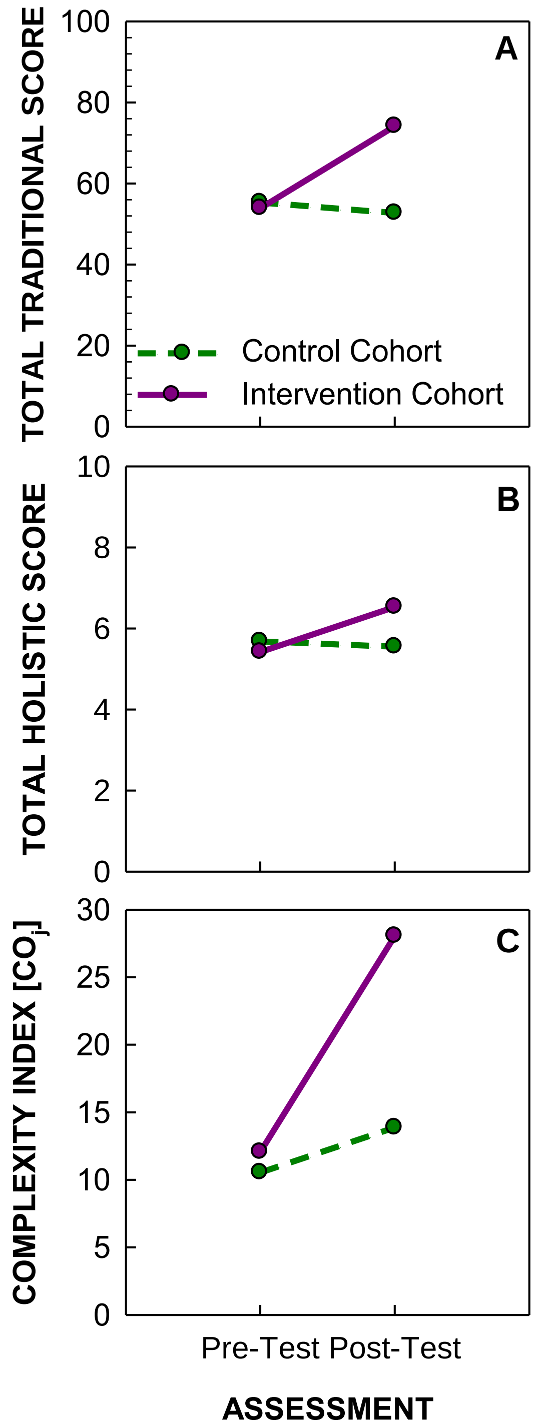

Figure 9.2. Summary of pre- and post-cmap scores from control and intervention cohorts determined using (A) traditional, (B) holistic, and (C) categorical scoring methods.

Comparison to Other Sustainability-Focused Courses

Based on Holistic Scores

Total holistic scores were slightly higher than reported for a similar study of a green engineering course. Borrego et al. [151] used the holistic approach to score 10 sustainability-related cmaps before and after a two-semester, inter-disciplinary green engineering course and found mean consensus scores to increase from 3.8 to 5.1 on a nine-point scale. In the current study, total holistic scores for the intervention cohort increased from 5.6 to 6.5 after completion of capstone design and the module. It is possible that the starting total scores, and consequently subsequent gains, were higher in the current study due to student completion of a sustainability-related course (CEE 3000: Civil Engineering Systems) prior to enrollment in capstone design [179]. In addition, some variability in scores may exist since the same set of judges was not used in both studies. Nevertheless, gains in sustainability knowledge, as gauged by the holistic approach, are broadly comparable to other studies.

Based on Categorical Scores

Cohort-level categorical metrics (Table 3.10) were also used to benchmark student performance in the sustainability module relative to that of students completing sustainability-focused courses administered in the UK. Segalàs et al. [118] found that students participating in courses employing innovative pedagogies demonstrated CO_{cohort} gains ranging from zero to 22.2 (average gain = 8.1), as compared to CO_{cohort} improvements ranging from zero to 9.4 (average gain = 4.5) for those enrolled in traditional courses [118]. In comparison, students participating in the current sustainability module demonstrated a CO_{cohort} gain of 12.4, which is well above the mean for traditional courses, but approximately half the gain of the most successful innovative course. Nevertheless, the fairly short sustainability module encouraged gains in student learning on par with other sustainability-focused courses incorporating active pedagogies.

This supports the ultimate conclusion of Segalàs et al. [118] that student sustainability learning is best facilitated through employment of community- and constructivist-based approaches.

Comparison to Sustainability Experts

Cohort-level categorical metrics were also used to compare intervention cmaps based on those compiled by experts. While it is acknowledged that the evolving and subjective nature of sustainability precludes existence of a "perfect" cmap [197, 227, 228], it is still useful to benchmark student knowledge based on expert perceptions. Coral [197] collected cmaps from 19 sustainability experts that exhibited a cohort-level complexity index of 24.8, which is only slightly higher than the value (CO_{cohort} = 22.8) determined for cmaps developed by CEE students after participating in the modified capstone course. As a result, the sustainability sessions allowed participants to make great strides towards developing more expert-level sustainability knowledge.

Comparing Learning Gains as Indicated by Concept Maps and Student Surveys

Although cmap scores suggest an overall improvement in students' conceptual understanding of sustainability, students' perceptions of their learning gains were not impacted by participation in the module. For instance, the percentage of students' whose abilities to "discuss the concept of sustainable development" were indistinguishable between the control and intervention cohorts (Table 9.5). Similarly, discrepancies between student perceptions and other assessment scores after engagement in active learning have also been reported in the literature [214]. Even so, learning gains demonstrated by cmap scores in the present study likely indicate true improvements in students' understanding of sustainability concepts, due to the previously shown cognitive validity of cmaps [143, 150], as well as the acceptable interrater reliability (Table 3.11) and convergent validity (Table 3.12-3.13) demonstrated for applied methods.

Impact of Module on Student Ability to Apply Sustainability Knowledge

Integration of the sustainability module into the capstone design course had limited impact on student sustainable design abilities, according to analysis of capstone reports and survey scores. Based on Student Sustainability Surveys, more students in the intervention cohort than the control cohort indicated improved confidences to meet some environmental ("use renewable resources"), social ("addresses community and stakeholder requests"), and sustainable design tools ("incorporates life cycle analysis") criteria (Table 9.6). While capstone design projects from the intervention cohort did not show improvements in the same design criteria, students participating in the module did develop designs that more extensively considered environmental ("minimizes natural resources depletion") and social ("considers local circumstances and cultures") design criteria (Table 9.4). As a result, integration of the sustainability module into capstone design may have had limited influence on students' abilities to address some sustainability considerations in their projects.

Despite some improvements in student abilities to address a few sustainable design criteria, the intervention cohort did not demonstrate greater gains in overall sustainable design capabilities. According to the Student Sustainability Surveys, there was no statistical difference between percentages of students indicating heightened confidences in their abilities to "develop sustainable solutions to engineering problems" based on cohort (Table 9.5). Indeed, with mean earned scores of approximately 1.0 (Table 9.4), both cohorts of students demonstrated only "developing" abilities to engage in sustainable design (Table 3.16). Thus, even with module integration, additional efforts are need to improve seniors' abilities to apply sustainability concepts during design.

Implications of Student Feedback for Future Implementations

Several strategies are suggested to improve dissemination of the individual module sessions, given the student feedback (Table 9.7). Specifically, since some students indicated that Session 2 was too rigid, it could be reformatted to encourage students to learn about sustainability themes through group discussion rather than structured talks (see *Chapter Ten*). While most students found the BedZED case study helpful, groups could be given the option of finding and analyzing an alternative case study that aligns more with their individual projects. Providing increased flexibility in module activities may foster improved student engagement in the future.

Importantly, efforts should be made to improve students' overall perceptions of the module. Many students indicated that the module should not be conducted in capstone design because it takes focus away from projects. One strategy for remediating the perceived disconnect between the module and semester projects is to initiate efforts to make sustainable design an explicit part of the final project grade. While students were provided with an opportunity to examine the sustainability of their own projects in Session 4, actual integration of sustainability into their final projects was up to the discretion of the group (and possibly the sponsors guiding the groups). Perhaps requiring sustainability to be addressed in projects may also lead to improvements in demonstrations of sustainable design abilities, which were largely not seen in the current implementation. In addition, Sessions 2 and 3 could be completed at the beginning of the semester to equip students with the knowledge and skills to fulfill the sustainability component of their final projects. Overall, while some improvements could enhance its effectiveness, the module has promising potential for improving student sustainability knowledge.

Limitations

The experimental design poses some limitations to the study. The design, a quasi-experimental, cohort control group design, usually has lower internal validity than a true experimental design. In educational research especially, experimental designs are often not feasible, due to the inability or ethical questions associated with randomly assigning students to control and treatment groups [241]. However, quasi-experimental designs, which are identical to experimental designs, except in the random assignment to groups, can still be used to establish causality, as long as threats to internal validity have been addressed [217]. One common compromise to internal validity is when the treatment group differs in some substantial way, other than exposure to the intended treatment, to the control group [215]. In the current study, this threat was minimized by using academic cohorts as groups, since cohorts have been suggested to differ only minimally in background and demographics [215-217]. Furthermore, cohort-based designs are useful for minimizing the initial selection biases that may be present in the nonequivalent comparison group designs [215]. In fact, the pre-cmap scores for the intervention and control cohorts were very similar, regardless of the applied scoring method (Figure 9.2). Thus, efforts were made to address the inherent limitations of the quasi-experimental design.

An additional limitation is the use of student-provided confidence scores as a measure of sustainability knowledge. Specifically, one drawback is that students may over-estimate their abilities [212-214]. Appropriately, student concept maps and capstone design projects were examined as more objective measures of students' conceptual knowledge and design capabilities, respectively.

Finally, outcomes of the concept-map-based assessments may not be reproducible, due to reliance on scoring by human judges. While the traditional method is fairly objective, the holistic approach requires judges to make somewhat subjective judgments about the comprehensiveness, organization, and correctness of cmaps, while the categorical approach dictates that judges assign cmap concepts according to a ten-category taxonomy. While guidelines from the literature were followed in application of the holistic [131] and categorical [118] scoring schemes, it is possible that results may vary some depending on the judges analyzing the cmaps. However, acceptable interrater reliability for the applied methodology, demonstrated by Krippendorff's alpha above 0.67

(Table 3.11), suggests that judges can arrive at precise scores, especially if they engage in a scoring calibration session, as was completed in the current study. In addition, key interpretations to the holistic and categorical guidelines were well-documented (Tables 3.8-3.9) in this study to promote reproducibility by other researchers.

Summary and Conclusions

An investigation was conducted to characterize the impacts of integrating a learning-cycle-based sustainability module into a CEE capstone design course on student sustainability knowledge. Changes in students' conceptual understanding and sustainable design abilities were inferred by analyzing student-generated concept maps and capstone design reports, respectively, as well as student perceptions surveys. After comparing learning gains for students enrolled in a traditional capstone course (control cohort) and a course modified to include a learning-cycle-based sustainability module (intervention cohort), the following conclusions were reached.

1. Participating in the sustainability module allowed students to increase their conceptual understanding of sustainability, as indicated by the significantly higher increases in traditional, holistic, and categorical cmap scores for students in the intervention as compared to the control cohort.
2. Engagement in module activities had little impact on students' overall sustainable design abilities, although heightened abilities to apply some environmental and social design criteria were observed.
3. Future module implementations should strive to ensure complete integration of the module into the course by requiring sustainability to be addressed in final projects, which may help alleviate the student-perceived disconnect between module activities and the capstone project.

While any educational intervention can always be improved, the module proves to be promising for enhancing student sustainability knowledge. As a result, the module can be implemented in other capstone courses to help students learn about and analyze sustainability in a design context. It is imperative that students be cognizant of and able to engage in sustainable design because they are the engineers that will be responsible for making critical decisions that will impact the sustainability (or un-sustainability) of future development projects.

CHAPTER TEN

IMPACTS OF IMPLEMENTING A LEARNING-CYCLE-BASED SUSTAINABILITY MODULE INTO A CEE CORNERSTONE DESIGN COURSE

Chapter Overview

The goal of this chapter is to examine the impacts of implementing a learning-cycle- and inquiry-based sustainability module (see *Chapter Eight*) into a cornerstone design course (Civil Engineering Systems) on student sustainability knowledge (Research Question 3.2; Table 1.2). Based on suggestions from seniors previously participating in the module (see *Chapter Nine*), alternative formats for Session 2, in which students learn about foundational sustainability concepts, were investigated. In the peer-lecture cohort (Civil Engineering Systems, Session A, Fall 2012), students learned about sustainability concepts by participating in in-class lectures taught by their group members. In the peer-discussion cohort (Civil Engineering Systems, Session B, Fall 2012), students were introduced to sustainability concepts by engaging in less-structured peer discussions. Changes in students' conceptual and applied knowledge were assessed using cmaps (Figure 3.6) and/or the Student Sustainability Survey (Figure 3.10, Table 3.19), and compared to learning gains for seniors having previously participated in the module (Research Question 3.3; Table 1.2). Results were used to address the following questions: (1) What are the differences between students' conceptual and applied learning gains for the peer-lecture and peer-discussion cohorts? (2) What are the differences between students' conceptual and applied learning gains for the cornerstone and capstone implementations of the module? (3) How should the sustainability module be implemented in the future?

Results

Comparing Peer-Lecture and Peer-Discussion Cohorts

Effectiveness of each the peer-lecture and peer-discussion versions of the sustainability module was investigated. Cmap scores and selected items from the Student Sustainability Survey were used to gauge changes in conceptual understanding, while the Student Sustainability Survey was used to monitor changes in students' sustainable design confidences.

Concept Map Scores

Traditional and Holistic Methods

Both traditional and holistic scoring methods revealed few differences between cmaps generated by peer-lecture and peer-discussion cornerstone cohorts (Tables 10.1-10.2). In fact, improvements in the breadth and depth of students' knowledge were similar, since no statistically significant interactions were found between the number of concepts, highest hierarchy, or comprehensiveness sub-scores by cohort. However, the connectedness of students' knowledge, as indicated by the number of cross-links, increased more ($p \leq 0.05$) for peer-lecture students ($\Delta_{\text{post-pre}} = +2.5$), as compared to their peer-discussion counterparts ($\Delta_{\text{post-pre}} = +0.6$). Conversely, changes in organization sub-scores, which also capture the structural complexity of student cmaps, were similar for both cohorts. Overall, increases in general cmap qualities, as quantified by the total traditional and total holistic scores, were not substantially different for the two groups of students. Even so, means for all traditional and holistic sub-scores increased between pre- and post-assessments, indicating that participation in either version of the module resulted in positive conceptual learning gains.

Table 10.1. Comparison between pre- and post-cmap scores determined using the traditional scoring approach for peer-lecture and peer-discussion cohorts [Mean (Standard Deviation)].

	Peer-Lecture Cohort (n = 53)		Peer-Discussion Cohort (n = 58)		Combined Cohorts (n = 111)		Repeated Measures ANOVA $F(1, 109)$		
	Pre	Post	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
NC	14.6 (5.5)	29.4 (10.4)	15.2 (5.0)	29.8 (12.0)	14.9 (5.2)	29.6 (11.2)	213.84***	0.13	0.01
HH[1]	4.2 (1.4)	5.4 (1.7)	4.0 (1.2)	5.5 (2.2)	4.1 (1.3)	5.5 (2.0)	55.68***	0.012	1.11
NCL	2.9 (3.8)	5.4 (3.5)	3.5 (2.7)	4.1 (3.5)	3.2 (3.2)	4.7 (3.5)	16.45***	0.49	5.72*
Total	61.9 (36.3)	104.8 (35.6)	66.0 (26.7)	94.6 (39.3)	64.0 (31.6)	99.5 (37.3)	80.27***	0.34	3.26

$^*p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

[1]HH post violates homogeneity of variances according to Levene's test. Chance of a Type I error small since $p << 0.05$ for significant main effect.

Table 10.2. Comparison between pre- and post-cmap scores determined using the holistic scoring approach for peer-lecture and peer-discussion cohorts [Mean (Standard Deviation)].

	Peer-Lecture Cohort (n = 53)		Peer-Discussion Cohort (n = 58)		Combined Cohorts (n = 111)		Repeated Measures ANOVA $F(1, 109)$		
	Pre	Post	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
Comp[1]	1.2 (0.4)	2.4 (0.6)	1.1 (0.3)	2.2 (0.5)	1.2 (0.4)	2.3 (0.5)	293.08***	3.20	0.120
Org[1]	1.2 (0.5)	1.8 (0.6)	1.3 (0.5)	1.8 (0.8)	1.3 (0.5)	1.8 (0.7)	53.44***	0.00	1.11
Corr	2.9 (0.3)	3.0 (0.0)	3.0 (0.2)	3.0 (0.0)	2.9 (0.2)	3.0 (0.0)	6.48*	0.901	0.901
Total	5.4 (0.8)	7.2 (0.9)	5.4 (0.6)	7.0 (0.9)	5.4 (0.7)	7.1 (0.9)	296.48***	0.520	1.52

$^*p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

[1]Comp pre and Org post violate homogeneity of variances according to Levene's test. Chance of a Type I error small since $p << 0.05$ for significant main effects.

Categorical Method

According to the categorical scoring method, changes in the content of student knowledge were similar for both the peer-lecture and peer-discussion cohorts. In fact, all students incorporated more social concepts in their post cmaps (38.0%) than in the pre-cmaps (30.4%) [$F(1, 109) = 16.58$, $p \leq 0.001$]. Similarly, economic category distributions were higher for post- (33.5%) as compared to pre-assessments (24.4%) [$F(1, 109) = 25.56$, $p \leq 0.001$]. Conversely, all post-cmaps contained less environmental concepts (28.6%) than did pre-cmaps (50.4%) [$F(1, 109) = 102.68$, $p \leq 0.001$]. As demonstrated in Figure 10.1, participating in either version of the module aided students in developing a more holistic understanding of sustainability, with knowledge shifting from being primarily environmentally-focused to having nearly equal emphasis on all three dimensions.

In addition to developing a more balanced repertoire of sustainability knowledge, participation in both versions of the module aided students in developing connections between concepts from different sustainability categories. Specifically, the student-level complexity index (CO_j) increased between pre- ($M = 14.8$) and post-assessments ($M = 58.4$), regardless of cohort [$F(1, 109) = 118.62$, $p \leq 0.001$], although the increase in CO_j was not different for the peer-lecture and peer-discussion cohort [$F(1, 109) = 0.01$; $p = 0.907$]. Thus, students in both the peer-lecture and peer-discussion cohorts were able to develop more complex knowledge networks by engaging in the module activities.

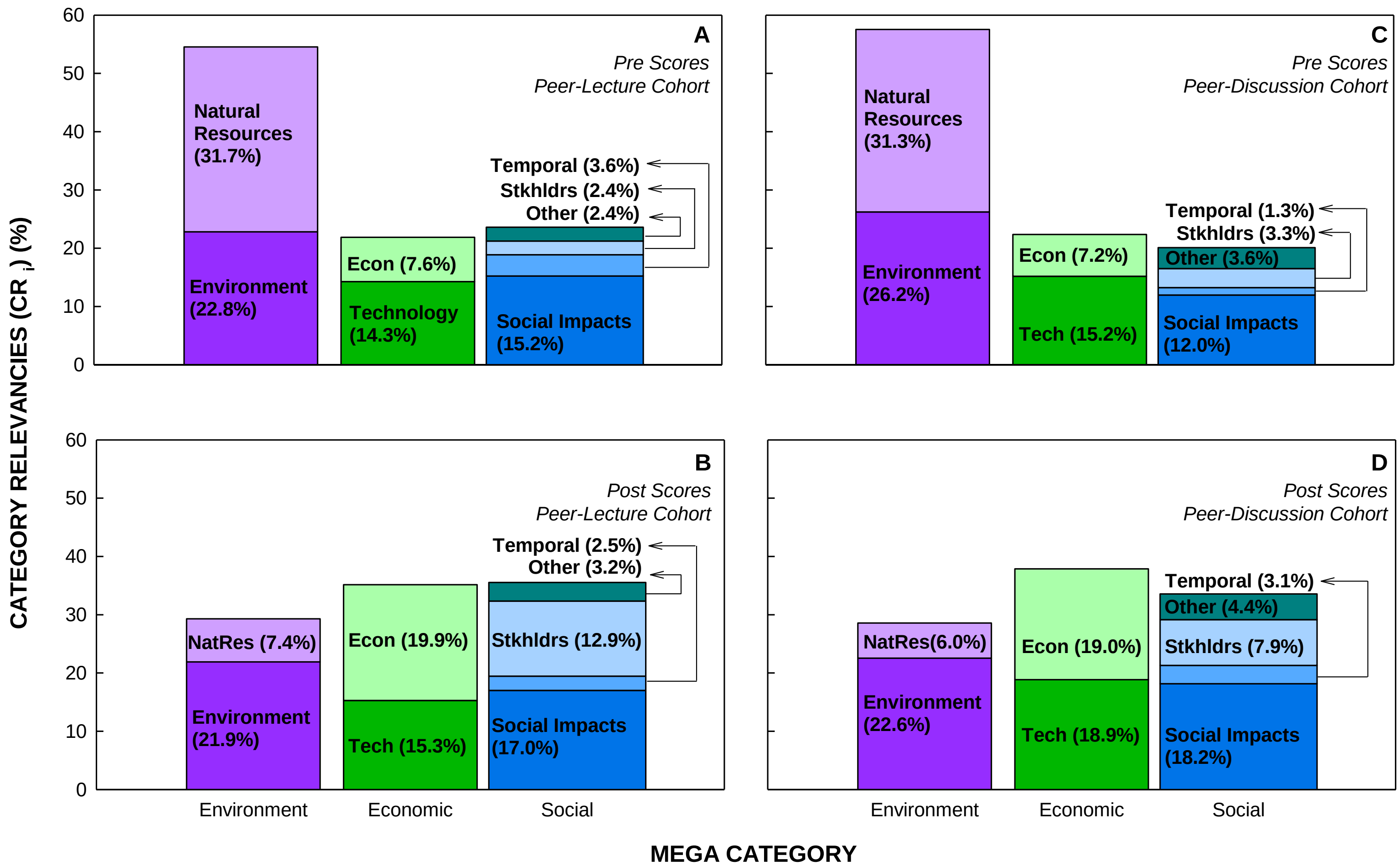

Figure 10.1. Comparison of (A) preliminary and (B) post category relevancies for students enrolled in the peer-lecture cohort, as well as (C) preliminary and (D) post category relevancies for students enrolled in the peer-discussion cohort ("Other" represents values, spatial imbalances, and education categories).

Student Sustainability Survey

In addition to examining student generated cmaps, items on the Student Sustainability Survey were used to gauge changes in students' perceptions of their sustainability knowledge. Students in both cohorts indicated increased confidences in their abilities to discuss sustainable development, as well as several dimensional aspects, after participating in the sessions (Table 10.3). Similarly, students also perceived themselves to have increased their abilities to "develop sustainable solutions to engineering problems (Table 10.3)," including designs that meet all of the sustainable design criteria (Table 10.4). Thus, regardless of whether students learned about foundational sustainability concepts through peer-lectures or peer-discussions, module participation increased confidences in their conceptual and applied sustainability knowledge.

When comparing the number of students positively impacted by module participation, few differences existed based on cohort. In fact, the percentage of students whose perceived conceptual understanding of sustainability was positively impacted by participation in the module was similar for both peer-lecture and peer-discussion cohorts (Table 10.3). Related to sustainable design capabilities, students' confidences to "develop sustainable solutions to engineering problems" were not significantly improved by participating in module activities (Table 10.4). However, a higher percentage of students participating in the peer-discussion version of the module were positively impacted in their perceived abilities to "incorporate systems analysis" into the design process. Even so, positive outcomes of the two module versions were mostly similar.

Table 10.3. Comparison between student-provided rankings to complete several tasks related to sustainable development (SD) before and after completion of the peer-lecture and peer-discussion versions of the sustainability module.

Survey Prompt: The statements below are related to sustainable development. Indicate how confident you are in your ability to complete the listed tasks.	Peer-Lecture Cohort (n = 52, df = 1) $[\pi_{6\text{-}7}]$ (%)			Peer-Discussion Cohort (n = 57, df = 1) $[\pi_{6\text{-}7}]$ (%)			Positively Impacted Students[1] (%) (n = 109, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Lecture Cohort	Discussion Cohort	Pearson χ^2
Develop sustainable solutions to engr problems.	13.5	48.1	15.56***	7.0	50.9	26.01***	38.5	43.9	0.327
Discuss the concept of SD.	17.3	75.0	31.01***	12.3	66.8	26.82***	57.7	59.6	0.043
Discuss connections between poverty, population, consumption, and env degradation.	11.5	51.9	17.12***	15.8	63.2	28.01***	46.2	47.4	0.016
Discuss economic factors that affect SD.	13.5	61.5	24.08***	5.3	71.9	37.06***	50.0	68.4	0.383
Discuss environmental factors that affect SD.	15.4	69.2	25.38***	14.0	68.4	28.35***	57.7	57.9	0.000
Discuss social factors that affect SD.	9.6	61.5	28.01***	14.0	66.7	29.07***	51.9	54.4	0.066
Evaluate a design based on sustainability criteria.	9.6	59.6	21.95***	8.8	61.4	27.36***	55.8	56.1	0.002

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Table 10.4. Comparison between student-provided rankings to complete several tasks related to sustainable design before and after completion of the peer-lecture and peer-discussion versions of the sustainability module.

Survey Prompt: The statements below are related to sustainable design. Indicate how important you think it is for engineers to be able to develop designs that meet the listed criteria. Also indicate how confident you are in your ability to develop designs that meet these criteria.	Peer-Lecture Cohort (n = 52, df = 1) $[\pi_{6\text{-}7}]$ (%)			Peer-Discussion Cohort (n = 57, df = 1) $[\pi_{6\text{-}7}]$ (%)			Positively Impacted Students[1] (%) (n = 109, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Lecture Cohort	Discussion Cohort	Pearson χ^2
Addresses community and stakeholder requests	13.5	53.8	17.12***	10.5	52.6	21.44***	46.2	45.6	0.21
Considers local circumstances and cultures	21.2	59.6	16.16***	19.3	59.6	15.78***	44.2	50.9	0.48
Incorporates life cycle analysis	9.6	40.4	13.61***	5.3	45.6	19.04***	34.6	45.6	1.37
Incorporates EIA tools	11.5	38.5	11.68***	10.5	49.1	18.08***	30.8	43.9	1.99
Incorporates systems analysis	5.8	44.2	19.10***	5.3	64.9	33.06***	40.4	61.4	4.81*
Uses innovative technologies to achieve sustainability.	11.5	48.1	16.53***	5.3	52.6	26.08***	40.4	49.1	0.84
Minimizes natural resource depletion	17.3	38.5	7.78**	19.3	49.1	11.34***	26.9	38.6	1.68
Prevents waste	17.3	50.0	14.58***	17.5	61.4	18.58***	36.5	52.6	2.85
Protects natural ecosystems	17.3	53.8	16.53***	15.8	54.4	16.88***	40.4	45.6	0.30
Protects human health and well-being	23.1	59.6	14.08***	14.0	70.2	31.07***	44.2	57.9	2.03
Uses inherently safe and benign materials	21.2	48.1	9.56**	17.5	52.6	15.01***	34.6	42.1	0.64
Uses renewable energy sources	15.4	48.1	13.32***	21.1	59.6	19.47***	38.5	42.1	0.15

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Student Feedback

<u>After Module Sessions</u>

Student ratings on the extent to which each session helped them achieve the relevant module objectives were largely similar for both cohorts. In general, just over 80% of peer-lecture and peer-discussion students “strongly agreed” that Session 2 helped them “broaden” and “deepen” their sustainability knowledge (Table 10.6). However, a higher percentage of students engaging in peer lectures (87.5%) “strongly agreed” that Session 2 “reinforced the complex and interrelated nature of sustainability” than students participating in peer-discussions (72.1%) ($p \leq 0.05$) (Table 10.6). In addition, about 80% and 70% of all students “strongly” indicated that Sessions 3 and 4, respectively, helped them to “analyze the impacts of a project on the economic, environmental, and social systems (Tables 10.7-10.8).” Also, approximately 60% of students “strongly” felt that Sessions 3 and 4 helped them see “how the 9 Principles of Sustainable Engineering can be applied during engineering design (Tables 10.7-10.8).” While Sessions 1 and 5 were intended to gather cmaps for assessment of the module itself, between 60% and 70% of students “strongly agreed” that the sessions helped them to examine their own sustainability knowledge (Tables 10.5-10.9). Overall, students felt that both peer-lecture and peer-discussion versions of the module aligned with module learning objectives.

In addition to evaluating activities, students also reflected (using a seven-point scale) on their overall experiences after sessions (Tables 10.5-10.9). For all sessions, between 60% and 70% of students “strongly” agreed that they enjoyed participating in the activities. Also, approximately 75% of students “strongly” indicated that each session should be implemented in future Civil Engineering Systems courses. For Session 2, no significant differences were found between responses of students participating in peer-lectures and those participating in peer-discussions.

Table 10.5. Quantitative student feedback after participation in Session 1 of the sustainability module entitled "Benchmarking Sustainability Knowledge Using Concept Maps."

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 54)	Peer-Discussion Cohort (n = 53)	Combined Cohorts (n = 107)	Chi-Square Test	
	$[\pi_{6-7}]$ (%)	$[\pi_{6-7}]$ (%)	$[\pi_{6-7}]$ (%)	χ^2 (1, n = 107)	p
Participation in Session 1 helped me to examine the breadth of concepts I understand related to sustainability.	68.5	60.4	64.5	0.075	0.785
Participation in Session 1 helped me to examine the depth of my sustainability knowledge.	70.4	58.5	64.5	1.648	0.199
Participation in Session 1 helped me to examine the interrelated nature of my sustainability knowledge.	70.4	64.2	67.3	0.470	0.493
I enjoyed participating in Session 1.	70.4	73.6	72.0	0.137	0.711
I would recommend Session 1 to be implemented in future CEE 3000 courses.	74.1	69.8	72.0	0.241	0.624

Table 10.6. Quantitative student feedback after participation in Session 2 of the sustainability module entitled "Conceptualizing Sustainability through Peer Lectures or Discussions."

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 56)	Peer-Discussion Cohort (n = 61)	Combined Cohorts (n = 117)	Chi-Square Test	
	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	χ^2 (1, n = 117)	p
Participation in Session 2 broadened my understanding of sustainability.	83.9	83.6	83.8	0.002	0.962
Participation in Session 2 deepened my understanding of sustainability.	83.9	82.0	82.9	0.079	0.778
Participation in Session 2 reinforced the complex and interrelated nature of the sustainability dimensions.	87.5	72.1	79.5	4.230	0.040*
I enjoyed participating in Session 2.	60.7	67.2	64.1	0.536	0.464
I would recommend Session 2 to be implemented in future CEE 3000 courses.	76.8	68.9	72.6	0.925	0.336

Table 10.7. Quantitative student feedback after participation in Session 3 of the sustainability module entitled "Examining Sustainable Design by Evaluating a Real-World Project."

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 52)	Peer-Discussion Cohort (n = 55)	Combined Cohorts (n = 107)	Chi-Square Test	
	[$\pi_{6\text{-}7}$] (%)	[$\pi_{6\text{-}7}$] (%)	[$\pi_{6\text{-}7}$] (%)	χ^2 (1, n = 107)	p
Participation in Session 3 improved my ability to analyze the impacts of a project on the economic, environmental, and social systems.	80.8	81.8	81.3	0.019	0.889
Participation in Session 3 improved my ability to assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	63.5	61.8	62.6	0.031	0.861
I enjoyed participating in Session 3.	69.2	61.8	65.4	0.649	0.420
I would recommend Session 3 to be implemented in future CEE 3000 courses.	78.8	70.9	74.8	0.893	0.345

Table 10.8. Quantitative student feedback after participation in Session 4 of the sustainability module entitled "Conducting Sustainability Analyses."

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 54)	Peer-Discussion Cohort (n = 62)	Combined Cohorts (n = 116)	Chi-Square Test	
	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	χ^2 (1, n = 116)	p
Participation in Session 4 improved my ability to analyze the impacts of a project on the economic, environmental, and social systems.	70.4	72.6	71.6	0.069	0.792
Participation in Session 4 improved my ability to assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	57.4	54.8	56.0	0.077	0.781
I enjoyed participating in Session 4.	57.4	69.4	63.8	1.784	0.182
I would recommend Session 4 to be implemented in future CEE 3000 courses.	75.9	72.6	74.1	0.169	0.682

Table 10.9. Quantitative student feedback after participation in Session 5 of the sustainability module entitled "Showcasing Sustainability Knowledge Using Concept Maps."

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 52)	Peer-Discussion Cohort (n = 60)	Combined Cohorts (n = 112)	Chi-Square Test	
	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	χ^2 (1, n = 112)	p
Participation in Session 5 helped me to examine the breadth of concepts I understand related to sustainability.	80.8	78.3	79.5	0.101	0.750
Participation in Session 5 helped me to examine the depth of my sustainability knowledge.	82.7	78.3	80.4	0.335	0.563
Participation in Session 5 helped me to examine the interrelated nature of my sustainability knowledge.	76.9	78.3	77.7	0.032	0.858
I can tell that my Session 5 concept map has improved, as compared to my Session 1 concept map.	86.5	81.7	83.9	0.490	0.484
I enjoyed participating in Session 5.	69.2	63.3	66.1	0.432	0.511
I would recommend Session 5 to be implemented in future CEE 3000 courses.	84.6	68.3	75.9	4.037	0.045*

*$p \leq 0.05$

After Module Completion

After completing the entire sustainability module, students reflected on the module as a whole (Table 10.10). Over 90% of all students "strongly agreed" that participating in the module helped them learn about sustainability concepts, while over 80% felt that module activities helped them learn about sustainable design. Also, nearly 80% of students "strongly agreed" that they enjoyed engaging in module activities. When asked to provide suggestions for improving the module, many students indicated that they thought no changes were needed (Table 10.11). Many students indicated that they very much enjoyed the Beddington Zero Energy Development case study and would like to see the use of more case studies in the module. Only a few students suggested that the workload was too high, although one participant admitted that he or she "[didn't] think that you [could lighten the workload] without sacrificing future students' knowledge base about sustainability" (Table 10.11). Based on closed- and open-ended student feedback, the module was effective for and well-received by cornerstone students.

Table 10.10. Quantitative student feedback after participating in the entire five-session sustainability module.

Survey Prompt: To what extent do you agree or disagree with the following statements?	Peer-Lecture Cohort (n = 55)	Peer-Discussion Cohort (n = 61)	Combined Cohorts (n = 116)	Chi-Square Test	
	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	$[\pi_{6\text{-}7}]$ (%)	χ^2 (1, n = 116)	p
Participating in the sustainability module helped me learn about sustainability concepts.	90.9	93.4	92.2	0.259	0.611
Participating in the sustainability module helped me learn about sustainable design.	85.5	83.6	84.5	0.075	0.784
I enjoyed participating in the sustainability module.	81.8	75.4	78.4	0.703	0.402

Table 10.11. Qualitative student feedback provided after participation in the entire five-part sustainability module.

General Positive Feedback

- "I thought overall there isn't a lot to improve on. It went very well. We used graphs, worksheets, and communicated what we learned with our peers. It helped a lot in preparing us for the final project too. I wouldn't change it. This module did a much better job teaching and understanding than any other class I've taken so far."
- "Sessions had laid back, relaxed tone to them while still accomplishing work. I have no suggestions as I enjoyed the module and learned a lot about sustainability."
- "I did not really see a way to improve the sustainability module. It was engaging and not boring at all. It also taught me a lot about different aspects of sustainability and how it affects us."
- "I don't have any suggestions. I think the module went really well. All the activities kept me engaged in class, and in what we were doing."

Constructive Feedback Requesting more Applications of Sustainable Design and/or Case Studies

- "More group work and work based on real-world current projects, as it really helped put some clarity and focus on understanding concepts when examining current sustainability case studies."
- "There should be more emphasis on the nine principles of sustainable engineering."
- "The case study on BedZED was very interesting to read, and the mini project was too because we got to see how designers implemented the concepts we were learning about. It would have been nice to read or learn about more real life examples and maybe some with shorter literature because BedZED took me an extremely long time to read. But it's really neat to see everything integrated and working so well."
- "The sustainability module has been great. I was able to learn key concepts in economic sustainability, social sustainability, environmental sustainability, and sustainability design in great detail. For improvement, going over more case studies would help."

Constructive Feedback Requesting Lighter Work Load

- "I would say lighten the work load, but I don't think you can without sacrificing future students' knowledge base for sustainability."
- "Reduction of information to only the concepts that you absolutely want us to know. Sorting through all of the available information was slightly overwhelming."

Comparing Cornerstone and Capstone Module Implementations

Learning gains for students participating in the cornerstone implementations of the sustainability module (peer-lecture and peer-discussion cohorts) were compared to those for senior CEE students (capstone intervention cohort, *Chapter Nine*). Specifically, cmap scores, Student Sustainability Survey responses, and module evaluations were compared between both groups.

Concept Map Scores

Traditional and Holistic Methods

Both traditional and holistic scoring methods reveal several differences between cmaps generated by cornerstone students and seniors participating in the sustainability module (Tables 10.12-10.13). First, improvements in knowledge breadth and depth, indicated by the number of concepts, highest hierarchy, and comprehensiveness sub-score, increased more for cornerstone students as compared to seniors ($p \leq 0.001$). However, improvements in the connectedness of students' knowledge were similar for both groups ($\Delta_{post\text{-}pre} = +1.5$). Due primarily to improvements in knowledge breadth and depth, both total traditional and holistic cmap scores improved more for cornerstone students than for seniors ($p \leq 0.05$). Even so, means for all traditional and holistic sub-scores increased between pre- and post-assessments, indicating that participation in the module resulted in positive learning gains.

Table 10.12. Comparison between pre- and post-cmap scores determined using the traditional scoring approach for capstone and cornerstone cohorts participating in the sustainability module [Mean (Standard Deviation)].

	Cornerstone Cohorts (n = 111)		Capstone Cohort (n = 72)		Repeated Measures ANOVA $F(1, 181)$		
	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
NC	14.9 (5.2)	29.6 (11.2)	14.2 (6.2)	19.3 (10.3)	171.63***	26.65***	40.59***
HH[1]	4.1 (1.3)	5.5 (2.0)	3.3 (1.2)	3.6 (1.3)	41.39***	49.31***	19.2***
NCL[1]	3.2 (3.2)	4.7 (3.5)	2.6 (3.2)	4.1 (6.6)	20.67***	1.38	0.00[2]
Total	64.0 (31.6)	99.5 (37.3)	53.9 (32.3)	74.1 (63.1)	69.08***	11.31***	5.13*

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]HH post and NCL post violate homogeneity of variances according to Levene's test. Chance of a Type I error small since $p \ll 0.05$ for significant main effect and interaction.

[2]Increase between NCL not significantly different between capstone cohort and cornerstone peer-lecture cohort, who showed greater increase in NCL than cornerstone peer-discussion cohort (Table 10.1).

Table 10.13. Comparison between pre- and post-cmap scores determined using the holistic scoring approach for capstone and cornerstone cohorts participating in the sustainability module [Mean (Standard Deviation)].

	Cornerstone Cohorts (n = 111)		Capstone Cohort (n = 72)		Repeated Measures ANOVA $F(1, 181)$		
	Pre	Post	Pre	Post	Test	Cohort	Test × Cohort
Comp[1]	1.2 (0.4)	2.3 (0.5)	1.3 (0.5)	1.8 (0.7)	246.44***	12.91***	33.94***
Org[1]	1.3 (0.5)	1.8 (0.7)	1.3 (0.5)	1.8 (0.8)	72.80***	0.13	0.11
Corr[1]	2.9 (0.2)	3.0 (0.0)	2.9 (0.3)	3.0 (0.0)	16.86***	2.01	2.01
Total	5.4 (0.7)	7.1 (0.9)	5.4 (0.8)	6.5 (1.0)	307.28***	7.12**	12.93***

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Comp pre, Org post, and Corr pre violate homogeneity of variances according to Levene's test. Chance of a Type I error small since p << 0.05 for significant main effects and interaction.

Categorical Method

According to the categorical scoring method, changes in the content of student knowledge varied somewhat between cornerstone and senior cohorts. While overall students included more economic concepts in their post- (*M* = 32.1%) versus their pre- (*M* = 26.3%) cmaps ($p \leq 0.001$), this increase was most substantial for cornerstone students ($p = 0.028$). Similarly, the environmental category distribution decreased in general between post- (*M* = 43.9%) and pre- (*M* = 29.8%) assessments ($p \leq 0.001$), although this decrease was highest for the cornerstone cohort ($p \leq 0.001$). Finally, students incorporated more social concepts into cmaps after (*M* = 42.3%) as compared to before (*M* = 32.4%) participation in the module ($p = 0.002$), however, this increase was not statistically different between student groups. As depicted in Figure 10.2, participating in the module aided students in developing a more holistic understanding of sustainability by reducing over-emphasis on environmentally-related concepts.

In addition to developing a more balanced inventory of sustainability knowledge, participation in the module aided both cohorts in developing connections between concepts from different sustainability categories. Specifically, the student-level complexity index (CO_j) increased between pre- (*M* = 13.5) and post-assessments (*M* = 43.2), regardless of cohort ($p \leq 0.001$). Even still, the increase in CO_j between pre and post cmap assessments was higher for cornerstone students ($\Delta_{post\text{-}pre} = 43.5$) as compared to seniors ($\Delta_{post\text{-}pre} = 15.9$) ($p \leq 0.001$). Overall, the module helped cornerstone students improve the complexity of their sustainability knowledge networks more than seniors.

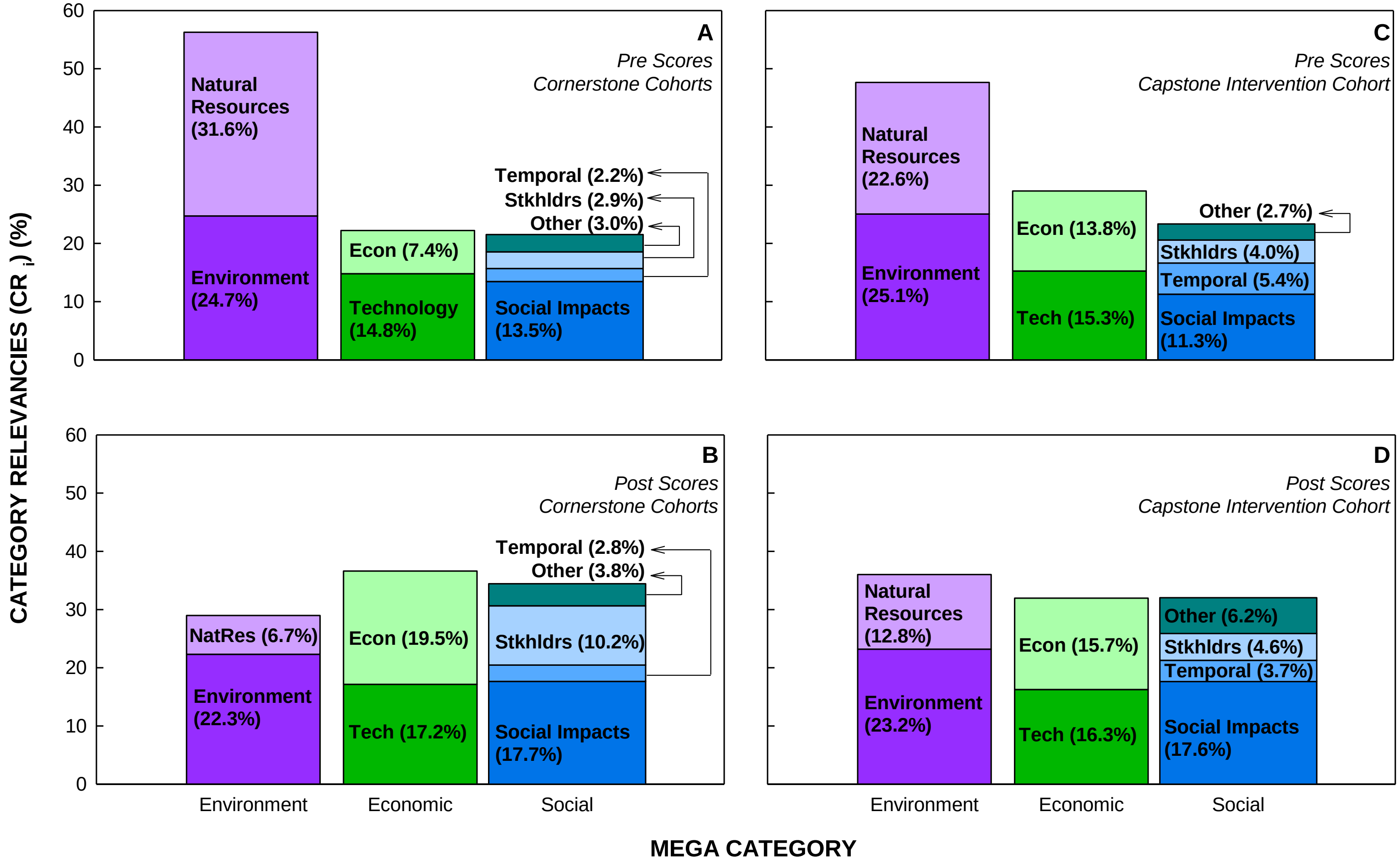

Figure 10.2. Comparison of (A) preliminary and (B) post category relevancies for students in cornerstone design cohorts, as well as (C) preliminary and (D) post category relevancies for students in the capstone design cohort ("Other" represents values, spatial imbalances, and education categories).

Student Sustainability Survey

Participation in the sustainability module improved cornerstone students' confidences in their conceptual sustainability knowledge more than capstone students' (Table 10.14). Both cohorts indicated improvements in their perceived abilities to "discuss the concept of sustainable development ($p \leq 0.05$)," although increases in confidence ratings were significantly higher for cornerstone students as compared to seniors ($p \leq 0.05$). However, members of the cornerstone cohorts also reported improved abilities to discuss sustainability dimensions and their interconnections, while capstone students indicated no such increases. As a result, according to students, the sustainability module had the greatest impact on conceptual learning gains when integrated into the cornerstone course.

Engagement in module activities improved both cornerstone students' and seniors' confidences in their abilities to create sustainable designs. Overall, both groups reported improvements in their abilities to "develop sustainable solutions to engineering problems," although increases were highest for the cornerstone cohorts (Table 10.14). When considering abilities to meet specific sustainable design criteria, all students reported gains in confidences for 10 out of the 12 surveyed criteria (Table 10.15). However, cornerstone students' confidences in their abilities to "consider local circumstances and cultures," incorporate systems analysis," "use innovative technologies to achieve sustainability," "prevent waste," "protect natural ecosystems," and "protect human health and well-being" improved significantly more than for seniors (Table 10.15). Overall, while the module positively impacted sustainable design abilities, greatest improvements were observed for the cornerstone students.

Table 10.14. Comparison between student-provided rankings to complete several tasks related to sustainable development (SD) before and after participation in the capstone and cornerstone implementations of the sustainability module.

Survey Prompt: The statements below are related to sustainable development. Indicate how confident you are in your ability to complete the listed tasks.	Cornerstone Cohorts (n = 109, df = 1) [$\pi_{6\text{-}7}$] (%)			Capstone Cohort (n = 84, df = 1) [$\pi_{6\text{-}7}$] (%)			Positively Impacted Students[1] (%) (n = 193, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Cornerstone Cohorts	Capstone Cohort	Pearson χ^2
Develop sustainable solutions to engr problems.	10.1	49.5	38.43***	27.4	43.0	4.88*	41.3	26.2	4.77*
Discuss the concept of SD.	14.7	70.6	55.54***	45.2	61.6	5.53*	58.7	31.0	14.70***
Discuss connections between poverty, population, consumption, and env degradation.	13.8	57.8	42.67***	35.7	44.2	1.24	46.8	23.8	10.77***
Discuss economic factors that affect SD.	9.2	67.0	59.24***	34.5	38.4	0.40	59.6	20.2	18.53***
Discuss environmental factors that affect SD.	14.7	68.8	51.96***	36.9	44.2	0.86	57.8	23.8	22.36***
Discuss social factors that affect SD.	11.9	64.2	55.07***	39.3	52.3	3.06	53.2	27.4	13.00***
Evaluate a design based on sustainability criteria.	9.2	60.6	47.52***	31.0	40.7	1.61	56.0	25.0	18.61***

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Table 10.15. Comparison between student-provided rankings to complete several tasks related to sustainable design before and after participation in the capstone and cornerstone implementations of the sustainability module.

Survey Prompt: The statements below are related to sustainable design. Indicate how important you think it is for engineers to be able to develop designs that meet the listed criteria. Also indicate how confident you are in your ability to develop designs that meet these criteria.	Cornerstone Cohorts (n = 109, df = 1) [$\pi_{6\text{-}7}$] (%)			Capstone Cohort (n = 84, df = 1) [$\pi_{6\text{-}7}$] (%)			Positively Impacted Students[1] (%) (n = 193, df = 1)		
	Pre	Post	[2]McNemar χ^2	Pre	Post	[2]McNemar χ^2	Cornerstone Cohorts	Capstone Cohort	Pearson χ^2
Addresses community and stakeholder requests	11.9	53.2	36.82***	38.1	58.3	7.12**	45.9	35.7	2.017
Considers local circumstances and cultures	20.2	59.6	30.31***	36.9	52.4	4.67*	47.7	31.0	5.530*
Incorporates life cycle analysis	7.3	43.1	31.04***	23.8	52.4	17.65***	40.4	34.5	0.689
Incorporates EIA tools	11.0	44.0	28.17***	26.2	50.0	11.06***	37.6	34.5	0.196
Incorporates systems analysis	5.5	55.0	50.28***	29.8	52.4	8.84**	51.4	36.9	4.013*
Uses innovative technologies to achieve sustainability.	8.3	50.5	40.69***	23.8	44.0	8.75**	45.0	31.0	3.915*
Minimizes natural resource depletion	18.3	44.0	17.82***	34.5	69.0	19.34***	33.0	44.0	2.450
Prevents waste	17.4	56.0	31.50***	36.9	51.2	4.60*	45.0	27.4	6.264*
Protects natural ecosystems	16.5	54.1	31.72***	39.3	53.6	4.34*	43.1	28.6	4.318*
Protects human health and well-being	18.3	65.1	42.64***	51.2	48.8	0.07	51.4	19.0	21.2***
Uses inherently safe and benign materials	19.3	50.5	23.12***	44.0	58.3	3.72	38.5	32.1	0.84
Uses renewable energy sources	18.3	54.1	31.04***	29.8	53.6	11.06***	40.4	34.5	0.69

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

[1]Percentage of students that indicated a preliminary score of less than six and a post score of six or greater (on a seven-point scale).

[2]McNemar tests used to compare pre- and post-scores within subjects. Test statistic calculated with Yates correction factor because some cells contained a frequency of less than 5.

Student Reflections

When examining closed-ended student feedback on the sustainability module, it was evident that cornerstone students (n = 116) found the activities to be more beneficial and enjoyable than did seniors (n = 88). Even though cmaps revealed that both groups of students learned quite a bit about sustainability, only 29.5% of seniors "strongly agreed" that the module helped them learn about relevant concepts, as compared to 92.9% of cornerstone students [$\chi^2(1, n = 204) = 86.68, p \leq 0.001$]. Similarly, most cornerstone students (84.5%) "strongly" felt that the module helped them learn about sustainable design, as compared to less than one-forth (19.3%) of seniors [$\chi^2(1, n = 204) = 83.40, p \leq 0.001$]. As a result, cornerstone students in general (78.4%) "strongly" asserted that they enjoyed participating in module activities, while very few seniors (15.9%) felt the same [$\chi^2(1, n = 204) = 78.35, p \leq 0.001$].

Discussion

Comparing Learning Impacts for Peer-Lecture and Peer-Discussion Cohorts

Impacts on Conceptual Knowledge

Both peer-lecture and peer-discussion cohorts showed improvements in overall conceptual understanding of sustainability, according to cmaps (Figure 10.3) and student surveys (Table 10.3). In fact, increases in students' total traditional ($\Delta_{post\text{-}pre}$ = +35.5) and total holistic ($\Delta_{post\text{-}pre}$ = +1.7) cmap scores were similar for both cohorts, as well as improvements in their confidences to "discuss the concept of sustainable development." Although the module was only composed of five sessions, the gain in holistic scores was comparable to the increase reported for students engaging in a two-semester, inter-disciplinary green engineering course ($\Delta_{post\text{-}pre}$ = +1.3) [151]. In addition, increases in the overall complexity of student cmaps, as quantified by the complexity index (CO_{cohort}), was also similar for both cohorts ($\Delta_{post\text{-}pre}$ = +39.9). This increase was slightly higher than the highest gain ($\Delta_{post\text{-}pre}$ = 22.2) reported for students completing a variety of sustainability-focused courses incorporating different types of active learning pedagogies [118]. Even further, the final score for cornerstone students (CO_{cohort} = 58.4) was higher than reported for a small group of sustainability experts (CO_{cohort} = 24.8) [197]. As a result, both versions of the sustainability module, despite their brevity, served to improve students' conceptual understanding of sustainability just as much as reports of full-length courses.

Examining specific aspects of student knowledge, including depth, breadth, connectedness, and balance, showed many similarities between cohorts. Not only were similar increases in the breadth and depth of student knowledge observed according to cmap scores (number of concepts, highest hierarchy, and comprehensiveness sub-scores) (Figure 10.3), but both cohorts also indicated corresponding increases in their confidences to discuss sustainability and related dimensional aspects (Table 10.3). Despite these similarities, the traditional cmap scoring method showed that students in the peer-lecture cohort demonstrated a greater increase in the number of cross-links included in their cmaps than their counterparts. This is a notable difference, since cross-links are indicators of connectedness and expert-like semantic networks [138]. However, the organization sub-score for the holistic method showed no such differences in improvements of cmap structure by cohorts. Even still, students felt equally as confident in their abilities to "describe the connections between poverty, population, consumption, and environmental degradation." Related to the balance of knowledge gained, all students showed shifts from recognizing primarily environmental concepts to embracing a more holistic perspective of sustainability that included economic and social dimensions. Overall, participation in both versions of the module served to improve the breadth, depth, and balance of student knowledge, although the peer-lecture cohort may have developed more connected knowledge networks that students from the peer-discussion cohort.

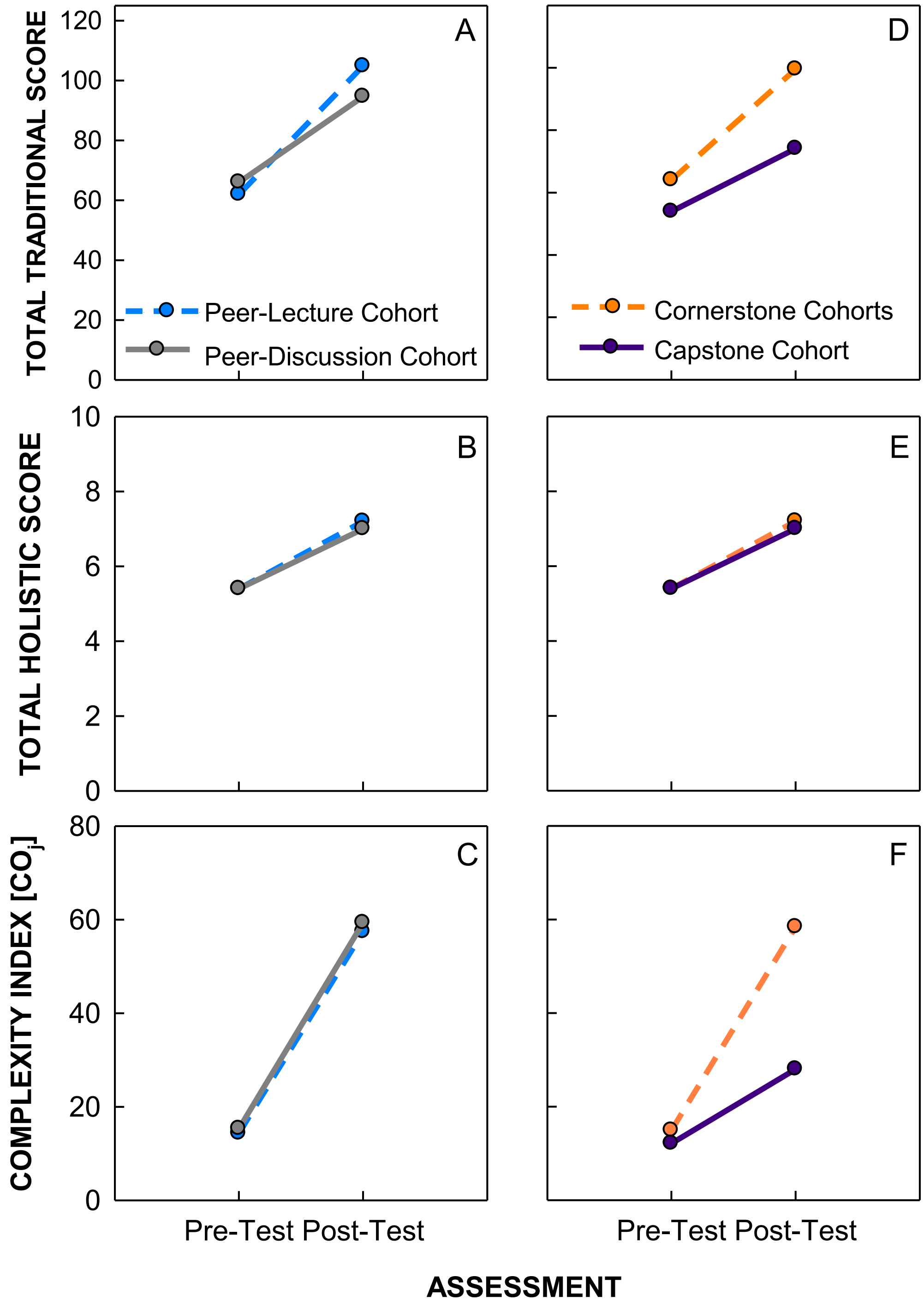

Figure 10.3. Comparison of (A) traditional, (B) holistic, and (C) categorical cmap scores between peer-lecture and peer-discussion cornerstone cohorts, as well as (D) traditional, (E) holistic, and (F) categorical cmap scores between cornerstone and capstone cohorts.

Impacts on Sustainable Design Abilities

Participation in both peer-lecture and peer-discussion versions of the module had positive impacts on students' confidences in sustainable design abilities (Tables 10.3-10.4). All students reported improved abilities to not only develop sustainable engineering solutions, but also to incorporate the 12 surveyed sustainable design criteria into their solutions. Among those criteria that most students felt "extremely confident" in their abilities to achieve were "protecting human health and well-being" and "considering local circumstances and cultures." In general, students were least confident in their abilities to "incorporate life cycle and environmental impact analyses" into the design process. Interestingly, peer-discussion students reported greater increases in their confidences to "incorporate systems analysis" into the design process than their counterparts in the peer-lecture cohort. Although this was the only criterion for which responses differed by cohort, it is substantial because one of the primary goals of the Civil Engineering Course itself was to help students develop systems thinking (see Appendix A). Thus, while the module aided students in developing sustainable design skills, the peer-discussion version may help students better perform in the cornerstone course itself.

Implications of Student Feedback

Although students had some suggestions for improving the module, their feedback was quite positive (Tables 10.5-10.11). Importantly, students indicated that each of the module sessions aligned with one or more of the four module learning objectives. Interestingly, students in the peer-lecture cohort felt that Session 2 helped them to "reinforce the complex and interrelated nature of sustainability" more than students participating in the peer-discussion group. Appropriately, peer-lecture students also demonstrated a greater increase in the number of cross-links in their cmaps than those participating in the peer-discussion version of Session 2. After reflecting on the module as a whole, approximately 80% of students "strongly" agreed that they enjoyed participating in the module. Among the most common requests from students was to incorporate additional case studies into the module. Those embarking on future implementations of the module could consider expanding Session 3: "Examining Sustainable Design by Evaluating a Real-World Project" to include multiple case studies.

Comparing Learning Impacts for Cornerstone and Capstone Cohorts

Impacts on Conceptual Knowledge

Participating in the module positively impacted both cornerstone students' and seniors' conceptual understanding of sustainability (Figure 10.3). In fact, overall quality of cmaps (total traditional, total holistic, and complexity indexes), including breadth and depth of knowledge (number of concepts, highest hierarchy, and comprehensiveness sub-scores) increased for all students over the course of the module. However, improvements were most substantial for cornerstone students. In addition, both groups demonstrated similar increases in knowledge connectedness (number of cross-links and organization sub-scores) after module participation. It is possible that improvements in seniors' scores were not as impressive because they had already developed a conceptual understanding of sustainability through their previous completion of the cornerstone course. While this is possible, initial cmap scores were similar for both cornerstone students and seniors, which supports that seniors had the same capacity for improvement as the cornerstone cohort.

While actual conceptual knowledge gains demonstrated in cmaps improved for both groups of students, cornerstone students demonstrated the highest gains in confidence scores (Table 10.14). Although all students indicated improvements in their overall abilities to discuss sustainable development, this increase was highest for cornerstone students. Even still, while both groups demonstrated improvements in depth, breadth, connectedness, and balance of knowledge depicted in cmaps, only cornerstone students reported corresponding increases in confidences in their abilities to discuss the dimensional and connected aspects of sustainability. Overall, cornerstone students recognized the learning benefits of the module while seniors largely did not.

Impacts on Sustainable Design Abilities

Both cornerstone and capstone students reported improved confidences in sustainable design abilities (Table 10.15). Beyond their perceived increased abilities to develop sustainable engineering solutions, both groups reported improved abilities to incorporate at least 10 of the 12 surveyed sustainable design criteria into their designs. While increases in confidence scores provided by cornerstone students were significantly higher than those reported by seniors for six of the criteria, this is potentially because initial scores were highest for capstone students. Overall, while both groups perceived substantial improvements in sustainable design abilities, cornerstone students likely had more capacity for change than did seniors.

Implications of Student Feedback

Overwhelmingly, student feedback was most supportive in the cornerstone cohort. In fact, the module was tested in the cornerstone course only after suggestions from capstone students that it would be more useful earlier in the curriculum (see *Chapter Nine*). Seniors suggested that participating in module activities conflicted with their desire to solely work on the semester projects. Rather, cornerstone students viewed the module as aiding them in completing their semester project. One student even commented that the module "...helped a lot in preparing [them] for the final project..." (Table 10.11). Even still, not only did more cornerstone design students indicate that the module helped them improve their knowledge about sustainability concepts and designs, but more also enjoyed engaging in the module than seniors. While gains in both conceptual and applied sustainability knowledge were documented for both cohorts, the module itself was best received and enjoyed by cornerstone students.

Insights for Future Application of Sustainability Module

Suggestions for Future Implementations in CEE at Georgia Tech

The sustainability module as it exists is most suitable for future implementation in the cornerstone design course (Civil Engineering Systems). The current study investigated two different methods for guiding students in learning foundational sustainability concepts: peer-lectures and peer-discussions. Both formats proved to elevate students' conceptual understanding of sustainability, as well as their confidences in their sustainability knowledge. Of notable differences between the two implementations, students participating in the peer-lecture cohort developed the most connected sustainability knowledge networks, while those in the peer-discussion cohort indicated higher increases in their confidences to engage in systems analysis during design. Connectedness of knowledge is important because it is indicative of expert knowledge and allows for retention and access of information, while developing systems thinking skills is one of the key learning outcomes of the cornerstone course itself. Given that general knowledge of sustainability is fundamental for engagement in systems thinking and ultimate success in the cornerstone course, there may be some benefit to opting for the peer-lecture version of the module. After all, if implemented at the beginning of the semester, students have much time after the module to continue refining their systems thinking skills. While the sustainability module certainly promoted more substantial improvements in learning for cornerstone design students, it could alternatively be integrated in capstone design. For suggestions on improving the module and its implementation for capstone design, please consult *Chapter Nine*.

Suggestions for Broad Implementation

While the sustainability module was developed for capstone and/or cornerstone design courses in CEE at Georgia Tech, it could be utilized by instructors elsewhere. Certainly, instructors of similar courses at other institutions could apply the module in its current form. In addition, the module could also be incorporated into other CEE courses, with semester projects that could serve as students' context for learning about sustainability. Not only does Session 4: Conducting Sustainability Analyses necessitate that students apply sustainability concepts to their semester projects, but lack of proper integration of the module with existing course material may lead to student resistance, as was potentially the case for the capstone intervention cohort (see *Chapter Nine*). Also, with some minor changes, the module could be made suitable for implementation in other engineering courses. Specifically, the Beddington Zero Energy Development Project case study that students analyze in Session 3 would need to be replaced with a discipline-specific example. Module materials, which would facilitate incorporation of activities into other courses, are available in Appendices H and I.

Limitations

The experimental design poses some limitations to the study. The design, a quasi-experimental, pretest-posttest design, usually has lower internal validity than a true experimental design. As discussed in *Chapter Nine,* experimental designs are often not feasible in educational research, due to the inability or ethical questions associated with randomly assigning students to control and treatment groups [241]. However, quasi-experimental designs, which are identical to experimental designs, except in the random assignment to groups, can still be used to establish causality, as long as threats to internal validity have been addressed [217]. One common compromise to internal validity is "history" or the fact that some other event other than the intervention could have caused differences in pre- and post-test scores. In the current study, assessments were given only five weeks apart, which makes the possibility of all students experiencing events that greatly improved their sustainability knowledge less likely. Another concern, particular to this study, is that students' sustainability knowledge would have increased in a traditional Civil Engineering Systems course without the integrated sustainability module. While it is nearly certain that participation in Civil Engineering Systems since its inception has guided students in improving their sustainability knowledge, the proposed sustainability module, at the least, does just the same. In addition, however, the module provides many added benefits. Of the most notable is the use of Kolb's learning cycle, which aids students in developing learning skills that they can utilize throughout their professional careers.

Additional limitations are similar to those discussed in *Chapter Nine* for the capstone implementation of the module. First, use of student-provided confidence scores as a measure of sustainability knowledge may be inaccurate, since there are many reports of students' over-reporting their knowledge [212-214]. Cmap scores were used to validate students' perceptions of conceptual learning gains. However, because the sustainable design rubric was not appropriate for the cornerstone semester project, only student perceptions were used to gauge impacts on sustainable design knowledge. Second, cmap scores may not be reproducible, since some methods, especially the holistic approach, may vary based on the judges selected. This shortcoming was addressed by using multiple scoring methods and training judges to promote acceptable interrater reliability (Krippendorff's alpha above 0.67, see Table 3.11).

Summary and Conclusions

An investigation was conducted to characterize the impacts of integrating two different versions of a learning-cycle-based sustainability module into CEE cornerstone design courses on student sustainability knowledge. All students participated in the module, as outlined in *Chapter Eight*, except that one class of students learned about sustainability concepts through peer lectures (peer-lecture cohort) and the second class of students learned about concepts through peer discussions (peer-discussion cohort). Changes in students' conceptual understanding and sustainable design abilities were inferred by analyzing student-generated concept maps and/or student perceptions surveys. The following conclusions were made based on the results.

1. Students in both the peer-lecture and peer-discussion cohorts demonstrated improvements in conceptual understanding of sustainability, although students in the peer-lecture cohort likely developed the most connected knowledge networks, which indicate progression towards expert-like sustainability knowledge.
2. Students in both the peer-lecture and peer-discussion cohorts indicated improved confidences in sustainable design abilities, although students in the peer-discussion cohort reported the most improved abilities to engage in systems analysis.
3. Cornerstone cohorts not only learned more about sustainability concepts than did seniros participating in module activities, but they also indicated the most substantial increases in knowledge confidences.
4. Although both cornerstone students and seniors showed substantial improvements in sustainable design confidences, cornerstone students reported more meaningful learning about 6 out of 12 sustainable design criteria.
5. The peer-lecture version of the sustainability module is suggested for future implementations in cornerstone design courses to help students develop connected and complex knowledge structures related to sustainability that will facilitate overall success in Civil Engineering Systems.

The learning-cycle-based sustainability module was shown to be useful for guiding students at various stages of their academic development in learning about sustainable development. While no single intervention is likely to transform an entire curriculum, the module does provide a relatively short, yet effective, means for initiating sustainability learning in a single course. Students completing this module could then be expected to possess the foundational knowledge needed to learn about sustainability applications in traditional engineering courses throughout the curriculum (horizontal integration). Overall, the module should be part of a larger and systematic plan to integrate sustainability throughout an undergraduate engineering curriculum.

CHAPTER ELEVEN

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

Project Conclusions

Inquiry #1: Assessing the Current Status of CEE Sustainability Education

A series of studies were conducted to assess the current status of CEE sustainability education at Georgia Tech for the purpose of guiding future reform efforts (Figure 11.1). Since students are important stakeholders in sustainability education, self-perceptions of their knowledge and educational experiences were gathered by administering a survey at the beginning of Fall 2011 and Spring 2012 capstone design courses (*Chapter Four*). The curriculum itself was examined using the STAUNCH® framework, both through an independent audit conducted by Organisational Sustainability and an internal audit completed by seniors enrolled in the Spring 2012 capstone course (*Chapter Five*). Unbiased accounts of students' conceptual understanding of sustainability were studied using student-generated concept maps (*Chapter Six*), while student sustainable design abilities were measured by applying the novel Sustainable Design Rubric to over 40 capstone design reports completed between 2002 and 2011 (*Chapter Seven*). The following conclusions were made based on the results.

1. Few students were extremely confident in their sustainability knowledge and sustainable design abilities, although most cited the importance of CEE courses for developing sustainability knowledge.
2. Efforts to integrate sustainability into the curriculum were evident; however, over-emphasis of the environmental dimension rendered the sustainability content unbalanced.

3. Student understanding about sustainability was limited in depth, breadth, and connectedness, while also demonstrating extreme over-emphasis of the environmental dimension.
4. During the design process, students primarily addressed only those sustainable design criteria that were required by course instructors or project sponsors, which primarily related to social sustainability.

Inquiry #2: Designing an Empirically-Informed and Pedagogically-Innovative Sustainability Module

A sustainability module was designed to improve student sustainability knowledge and design abilities (Figure 11.1). First, an extensive review of literature related to sustainability, sustainable engineering, and sustainability education (*Chapter Two*) was conducted. In addition, deficiencies highlighted during curricular (*Chapter Five*) and student knowledge assessments (*Chapter Six* and *Chapter Seven*) were considered. Afterward, a draft module was composed and distributed to an expert panel to elicit feedback (*Chapter Eight*). Important elements of the resulting five-part sustainability module are summarized below.

1. The module was designed to present sustainability holistically by equally emphasizing the economic, environmental, and social dimensions.
2. Foremost, the module was intended to *enrich* the knowledge of students' who have a correct, but incomplete, understanding of sustainability.
3. The module was deliberately designed to follow Kolb's learning cycle to encourage students to build on a conceptual understanding of sustainability before practicing sustainable design skills.

Inquiry #3: Investigating Impacts of Integrating the Sustainability Module into CEE Courses

After design of the five-part, learning-cycle-based sustainability module, its impacts on student learning were investigated in CEE courses (Figure 11.1). First, learning gains were compared between a traditional capstone design course and one modified to incorporate the sustainability module (*Chapter Nine*). Second, two versions (peer-lecture and peer-discussion) of the module were implemented into cornerstone design courses (Civil Engineering Systems), based on the recommendations of previous module participants (*Chapter Ten*). Module impacts on conceptual knowledge and sustainable design abilities were measured using student surveys, concept maps, and/or the Sustainable Design Rubric. The following conclusions were made based on the results.

1. After participating in the module, capstone students demonstrated gains in conceptual knowledge and increased abilities to meet select environmental and social design criteria, although they expressed dissatisfaction with the experience.
2. After participating in peer-lecture and peer-discussion versions of the module, cornerstone students, who greatly enjoyed the activities, demonstrated significant improvements in conceptual knowledge and sustainable design confidences.
3. Since gains in both conceptual knowledge and sustainable design confidences were greater for cornerstone students, as compared to capstone students, the sustainability module was deemed most suitable for integration into CEE cornerstone design courses.

Inquiry #1: Examine the current status of CEE sustainability education.

What do students' perspectives reveal about sustainability education?
Few students were extremely confident in their sustainability knowledge and sustainable design abilities, although most cited the importance of CEE courses for sustainability learning.

To what extent is sustainability content integrated into the CEE curriculum?
Efforts to integrate sustainability into the curriculum were evident; however, over-emphasis of the environmental dimension made the current content unbalanced.

How advanced is students' conceptual understanding of sustainability?
Students' understanding about sustainability was limited in depth, breadth, and connectedness, while also over-emphasizing the environmental dimension.

How proficient are CEE seniors in their abilities to engage in sustainable design?
In capstone design projects, students primarily addressed only those sustainable design criteria required by their project sponsors, which primarily related to social sustainability.

Inquiry #2: Design an empirically-informed and pedagogically-innovative sustainability module.

How should an educational intervention be designed to be sensitive to the results of curricular assessments?
The module was designed to present sustainability holistically, by equally emphasizing the economic, environmental, and social dimensions.

How should an educational intervention be designed to be sensitive to the results of student knowledge assessments?
The module was intended to enrich the knowledge of students who have a correct, but incomplete, understanding of sustainability.

In what ways can an intervention incorporate best practices in teaching and learning?
The module was deliberately designed to follow Kolb's learning cycle to encourage students to build a conceptual understanding of sustainability before improving sustainable design skills.

Inquiry #3: Investigate the impacts of integrating the sustainability module into select CEE courses.

To what extent can integration of a learning-cycle-based sustainability module into a CEE capstone design course improve student sustainability knowledge?
After participating in the module, capstone students demonstrated gains in conceptual knowledge and increased abilities to meet select environmental and social design criteria, although they expressed dissatisfaction with the experience.

To what extent can integration of a learning-cycle-based sustainability module into a CEE cornerstone design course improve student sustainability knowledge?
After participating in peer-lecture and peer-discussion versions of the module, cornerstone students, who greatly enjoyed the activities, demonstrated significant improvements in conceptual knowledge and sustainable design confidences.

Is the sustainability module best suited for integration into CEE capstone or cornerstone courses?
Since gains in both conceptual knowledge and sustainable design confidences were greater for cornerstone students, as compared to seniors, the sustainability module was deemed to be best suited for integration into CEE cornerstone design courses.

Figure 11.1. Summary of research questions and corresponding conclusions.

Contributions

Contribution #1: Curricular Assessment Methods

Especially given the extent to which curricular quality contributes to student learning about sustainability, it is important to have methods for systematically examining the content of a curriculum. STAUNCH® provides a unique framework for assessing the extent to which sustainability topics are integrated into a set of courses [125]. While the STAUNCH® tool certainly provides useful data for planning and/or evaluating reform efforts, acquisition of the software itself may be expensive, and scoring of each course requires specialized training [242]. In the current study (*Chapter Five*), the Student Curriculum Survey was administered to a group of CEE seniors to allow them to rate the extent, on a seven-point scale, to which each of the 40 key STAUNCH® topics were covered by the CEE courses that they had completed. Interestingly, the results of the external STAUNCH® and internal student assessments were fairly similar, with both parties showing that the curriculum emphasized environmental sustainability over economic and social issues. As a result, this study supports that a student survey based on the STAUNCH® framework may be a suitable alternative for those program leaders wishing to conduct preliminary curricular analyses who do not have access to the STAUNCH® tool itself. Even if the tool is available, conducting a relatively simple student survey may be used to establish validity of results, since some authors [21, 194] have argued that reliance of STAUNCH® on syllabi content rather than actual classroom events may compromise results.

Contribution #2: Sustainability Knowledge Assessment Methods

Effectively training engineers to be cognizant of sustainability requires employment of valid and reliable measures of students' sustainability knowledge. Examining students' understanding of sustainability is difficult, due to the broad, complex, somewhat subjective, and constantly-evolving nature of the domain. Many authors in the literature rely on surveys to collect students' self-reports of their cognitive abilities [9, 132, 134, 135]. However, student survey responses are known to over-state actual knowledge [212-214], as was demonstrated in the current work (*Chapter Six*). Consequently, cmaps were used as a more objective measure of student sustainability knowledge (*Chapter Six*). While reports of using cmaps to examine knowledge of a particular domain are not novel in the literature [150], many cite infeasibility of cmaps as assessment tools due to difficulties in actually scoring the constructs [131, 148, 149]. Indeed, most studies using cmaps to capture student sustainability knowledge either do not consider the interrater reliability of their scoring methods [118], demonstrate the feasibility of their methods for only a very small sample of cmaps [151], and/or only use one cmap scoring method [118, 151]. Consequently, the present work is the first that demonstrates not only acceptable interrater reliability, but also the feasibility and similarity of three different scoring methods (traditional, holistic, and categorical approaches). Hopefully the methods presented here for obtaining and scoring student sustainability cmaps will guide other researchers and program leaders in conducting objective sustainability knowledge assessments.

Contribution #3: Sustainable Design Rubric

While methods are certainly needed to characterize students' conceptual understanding of sustainability, it is especially paramount to be able to measure engineering students' abilities to engage in sustainable deign. Reports of systematically assessing students' abilities to apply sustainability concepts in design have not been reported in the literature. Consequently, one of the aims of the current study was to develop a method for examining the extent to which students address sustainability in design projects as an indicator of students' overall sustainable design abilities. While a variety of metrics are available for quantifying the sustainability of large infrastructure projects [164, 198], many of these systems are inappropriate for student projects (See

Chapter Two for more details). As a result, the Sustainable Design Rubric, composed of 16 sustainable design criteria and two rating scales was created (*Chapter Seven*). While the rubric was extensively applied to CEE student projects at Georgia Tech, it could be applied to projects representative of almost any engineering discipline at any institution, since sustainable design criteria were based on the universal Nine Principles of Sustainable Engineering [58].

Contribution #4: Empirically-Informed and Pedagogically-Innovative Sustainability Module

In addition to methods for curricular, student knowledge, and student sustainable design capabilities assessments, a five-part, learning-cycle-based sustainability module was developed and empirically-validated to enhance student learning about sustainability. The module exploits active and experiential pedagogies, which have been shown to encourage student learning in a variety of domains [104], including sustainability [118]. Although the module was developed based on curricular and student knowledge deficiencies in CEE at Georgia Tech, elements such as aiding students in developing a comprehensive, balanced, and connected sustainability knowledge network are advantageous for students everywhere [243]. Even still, the module was demonstrated to positively enhance conceptual understanding of sustainability for students at a variety of stages in their academic careers (*Chapter Nine* and *Chapter Ten*). While developed for CEE students, small modifications could render the module applicable for a variety of engineering disciplines.

Future Work

Future Work #1: Widespread Application of Concept Map Assessments

Use of cmaps to characterize sustainability knowledge for a variety of different students and professionals would be a particularly interesting area of future work. First, examining cmaps with more variability will aid in conclusively establishing the potential for interrater reliability for each the traditional, holistic, and categorical scoring approaches. In the current study, cmaps were largely similar, since they were constructed by students with similar previous educational experiences related to sustainability. As a result, achieving acceptable interrater reliability was very feasible.

Even still, collecting and analyzing sustainability cmaps from a variety of experts, including academics and industry professionals, could be used to identify that information which is essential for students to become properly-equipped sustainable engineers. In addition, a large database of expert cmaps could be used to provide benchmark scores for which to judge undergraduate constructs. Although Segalas [117] examined expert cmaps, the sample was relatively small and only the categorical method was employed for scoring. Widespread application of concept-map-based sustainability knowledge assessments would be especially feasible through development of automated cmaps scoring programs.

Future Work #2: Use of the Sustainable Design Rubric to Qualitatively Study Capstone Design Groups

While the sustainable design rubric was applied to capstone design reports in the current work, an exciting extension would be to use it as a lens for qualitatively examining student and professional design groups throughout the design process. For students and experts, important and final design decisions are represented in project reports, although reports may or may not include all of the preliminary designs developed and decisions made by collaborators. As a result, rather than simply judging sustainable design abilities based on the final written reports, important insights may be gained through observations and/or interviews conducted throughout each phase of design. Using this approach for student capstone projects may aid in identifying barriers to and strategies for improving student incorporation of sustainability during design. Similar studies centered on professional design teams may allow for sustainable design strategies than can be transferred from the "real-world" into the classroom.

Future Work #3: Transferability of the Learning-Cycle-Based Sustainability Module

While the sustainability module was demonstrated to be effective for various groups of CEE students at Georgia Tech, additional work is needed to examine the transferability of these results. For instance, the module could be implemented in other CEE programs, or potentially in other engineering disciplines. Other interesting applications may be use of the module in high school courses or professional development courses for practicing engineers. In any of these scenarios, a variety of assessment measures, including surveys, concept maps, and the Sustainable Design Rubric, are available for quantifying module effectiveness.

APPENDIX A
SELECTED CIVIL AND ENVIRONMENTAL ENGINEERING COURSE SYLLABI

Included in Appendix A are course syllabi for the Civil Engineering Systems (CEE 3000) and Sustainable Engineering (CEE 4803B) courses offered at Georgia Tech. As discussed in *Chapter Three*, these two courses contribute to vertical integration of sustainability into the CEE curriculum.

CEE 3000A: CIVIL ENGINEERING SYSTEMS

Fall 2012; Location: Instr Ctr 205;

Time: TR 9:35-10:55 AM; Credits: 3 hours

Instructor
Franklin Gbologah Ph.D. Candidate, CEE Email: franklin.gbologah@gatech.edu Office Hours: By appointment
Co-Instructors
Dr. Lisa Rosenstein Office: SEB 325 Phone: 404-385-0347 Email: lisa.rosenstein@ce.gatech.edu Office Hours: By appointment URL:http://www.ce.gatech.edu/Faculty-Staff/faculty-listing **Dr. Ann Xu** Office: SEB 223 Email: yanzhi.xu@ce.gatech.edu
Teaching Assistant
Mary Katharine Watson Ph.D. Candidate, CEE Email: mwatson8@mail.gatech.edu

Course Description

This course introduces students to a Sustainable Engineering (SE) approach for planning, design, implementation, operation and renewal of civil engineering systems. The concept of sustainability is introduced as the operating paradigm for making decisions over the lifecycle of civil engineered facilities. Sustainability is concerned with continued progress and development of human communities while ensuring preservation of the natural and human environment to enable such development to continue. The *systems approach* is introduced as essential for SE, in how problems are defined, how analysis tools are used to evaluate the performance of facilities and services, how benefits, costs and risks are incorporated into decision-making, how the natural environment and social equity are considered; how facilities are operated and maintained after implementation, and renewed at the end of their useful lives.

Course Evaluation

The course grade is based on performance in four (possibly five) areas. With a 90% average or higher at the end of the semester, you will be exempt from taking the final exam.

1 Quizzes 30%
2 Homework Assignments 25%
3 Project Report/Team Presentation 20%
4 Communications Assignments 10%
5 Participation 5%
6 Final Exam 10%

Course Grading Scheme
A – 90.00   B – 80.00   C – 70.00   D – 60.00

Academic Integrity/ Course Conduct
This Georgia Tech Academic Honor Code is the standard of conduct for this course. The Honor
Code is available at http://www.honor.gatech.edu/. Unauthorized use of any previous semester course materials (quizzes, homework, projects, etc.), other than those provided by the instructor, is prohibited in this course. Using unauthorized materials will be considered a direct violation of academic policy and will be dealt with according to the GT Honor Code. Furthermore, **plagiarism** is unacceptable in this or any course. Plagiarizing is defined by Webster's as "to steal and pass off (the ideas or words of another) as one's own; use (another's production) without crediting the source." If caught plagiarizing, you will be dealt with according to the GT Academic Honor Code. For information on how to properly credit other authors in your assessments, please consult the ASCE Author's Guide (www.asce.org/Content.aspx?id=18107).

Course Organization
The course is organized into four modules as follows:

Module 1: Sustainable Engineering and the Systems Approach
What is sustainability? How is it defined for civil engineered systems? What issues today make such a paradigm necessary for civil and environmental engineers? What are the present limitations with sustainability as an operational framework? What is a system? What is the systems approach? How does it relate to Sustainable Engineering in planning, design, project implementation, operations and renewal of civil engineered systems? How do engineers plan for systems? How do they represent systems to analyze their performance? How do we address the social and environmental impacts of systems? How do we systematically approach infrastructure renewal?

Module 2: Mathematical Tools and Systems Performance Analysis
What techniques can be used to analyze the technical performance of systems? Methods presented include optimization by calculus, linear programming, queuing theory,

computer simulation, probability and statistics for addressing uncertainty. What are the strengths and limitations of these techniques in the sustainability paradigm?

Module 3: Economic Decision-Making Tools and Project Evaluation

How do engineers identify the "best" among competing alternatives? What techniques can be used for such comparisons, e.g., net present worth, benefit-cost ratios, internal rates of return?

How do we consider non-monetary benefits and costs in our assessment? What types of assessments are conducted to capture environmental and social impacts? What types of mitigation strategies are used to manage environmental and social impacts?

Module 4: Project Presentations and Course Summary

The final lecture periods will be used for project presentations. Project presentations are a critical component of your engineering communications education. Your attendance will contribute to your grade for the oral communications component of this course. You are expected to attend and participate in **all** presentations in order to obtain full credit for this module of the course. During the oral presentations, you can earn bonus points for thoughtful questions that demonstrate a thorough understanding of the course material.

Engineering Communication

An important objective of this course is to develop basic skills in Engineering Communication. Homework and project presentations are designed to provide opportunities for this development, and will be partially graded on the student's ability to communicate effectively. Dr. Lisa Rosenstein, the School of Civil and Environmental Engineering's expert in Engineering Communication, will participate in this course and should be viewed as an important resource in developing written, oral and visual presentations.

Library Information Skills

Another important objective of this course is to develop basic library information and research skills (manual and electronic). Again, the project is designed to develop and assess these skills. In particular, the quality, range and balance of information sources used in the project will be evaluated. Ms. Lisha Li, the Civil Engineering Librarian for the Institute, will participate in the course by presenting a workshop on the basics of Library Information and Research Skills and should be considered an important resource as you develop your written reports. She can be reached at lisha.li@library.gatech.edu or 404-385-7185.

Course Web

The course web pages are located at https://t-square.gatech.edu/portal. Course handouts, lecture notes, homework assignments, exam solutions and other resources will be posted on the web.

Course Outcomes

The School of Civil and Environmental Engineering has adopted a set of desired outcomes for the undergraduate education program. This course is designed to meet the following outcomes:

1) Understanding civil engineering solutions in a global, societal and environmental context, consistent with the principles of sustainable development
2) Solving engineering problems by applying fundamental knowledge of math, science and engineering
3) Identifying, formulating and solving civil engineering problems that meet specified performance, cost, time, safety and other quality needs and objectives
4) Working and communicating effectively both individually and within multidisciplinary teams
5) Obtaining a solid understanding of professional and ethical responsibility, and recognition of the need for and ability to engage in life-long learning
6) Experiencing an academic environment that facilitates and encourages learning and retention

Course Objectives

Upon completion of this course, the student should be able to:

1) Explain how the concept of sustainability can be applied in the planning, design, project implementation, operation and renewal of civil engineered facilities
2) Evaluate quantitatively the performance of civil engineering systems and discuss the strengths and limitations of such evaluations
3) Use engineering/economic decision making tools to identify the best economic project alternative and discuss the limitations of such tools for incorporating environmental and social impacts in lifecycle decision making for facilities
4) Discuss approaches for incorporating environmental and social impacts in the planning, design and operation of engineering projects
5) Apply performance analysis, economic decision making, environmental and social impact analysis tools in an integrated manner to comparatively assess the quality of different civil engineered facilities
6) Discuss and apply various approaches to address uncertainty in systems analysis, and
7) Demonstrate the basics of professional technical communications: written, oral and visual.

Policies on Homework and Exams
Please note that all assignments **must** be handed in on the due date. Only medical reasons will be considered for late assignments. Only in extreme cases will late homework be accepted with a penalty. In addition, personal trips must be scheduled around exams as exams **will not** be rescheduled to accommodate early trips home or any other trips of a personal nature.

Course Reader
The course reader is a compilation of articles and book chapters on civil engineering systems and sustainability. The reader is required for the course and is available at the *Engineer's Bookstore* (748 Marietta Street). Additional material will be given out to supplement the reader.

Description of Assessments
There will be five homework assignments in this course, which will provide practice for applying the tools and analysis methods discussed in class and in the readings. Each problem will be graded along the following general guidelines:
· A student will not be awarded any point for problems that were not attempted
· A student will be awarded 20 percent of the points for attempting a problem, even if his/her answer is wrong.
· A student will be awarded 60 percent of the points for having the right approach/interpretation but will a few errors

· A student will be awarded 90 percent of the points for providing a nearly correct solution. A nearly correct solution is one in which the error(s) is/are due to computation only.
· A student will be awarded all the points available for a correct solution to the problem

Please note the following to avoid deductions for the homework and quizzes:
· Missing or wrong units will result in a 10 percent point deduction
· Please round of all your answers which are not whole numbers or integers to 4 decimal places.

Improper rounding off can attract a 10 percent point deduction
· The logical steps that you use to solve problems are very important to help me assess your understanding of concepts. Please underline all answers. Please provide well a well organized, clearly written, step-by-step logic used in solving the problem. Problem solutions that are presented in a disorganized way will incur a 20 percent point deduction.

Students are expected to come to class prepared; completing the reading assignments beforehand. Students are also expected to participate in class – by being ready to discuss reading assignments, taking notes, volunteering to answer questions, working in groups or individually to solve problems, etc.

Communications Assignments – To practice the communication skills covered in Dr. Rosenstein's workshops, there will be two individual assignments (Written Communications and Visual Communications) and one team assignment (Oral Communications – Presentation Slides). Dr. Rosenstein will collect and grade these assignments. Please consult her with any questions regarding these assignments.

Quizzes
There will be three or quizzes, throughout the semester. Quiz 1 will cover Modules 1 & 2. Quiz 2 and Quiz 3 will cover content from Module 3. There will also be a

Final Exam
There will be an ***optional*** final exam that can be taken to raise your course grade. This exam will cover all contents discussed in the course of the lecture.

Team Project: Infrastructure System Analysis
During the first couple of weeks of class, students will be assigned to or allowed to self select teams of 4-5.

Each team will use the systems approach to analyze and assess the sustainability of a completed or nearly completed civil engineering infrastructure project. Students will need to synthesize information from various sources and utilize tools and methods learned over the course of the semester. Each team will produce a 15-page analysis paper and give a 15-minute presentation that succinctly presents their findings, providing sufficient support for all arguments. Each team will also have a 5-minute Q&A time. Deliverables will be spread out over the semester to allow for periodic feedback and opportunities for self-assessment. Specific directions will be given for each deliverable.

Re-grade Requests
All requests for re-grades on homework and quizzes must be submitted within one week after they are returned. If you want to request a re-grade, you must submit your graded assignment along with a short statement that (1) states which problems should be re-graded, and (2) ***clearly outlines why you believe your answer is correct / you deserve additional points***. The instructors reserve the right to re-grade your entire assignment, so note that it is possible your grade may go down after the re-grade.

Sustainability Module

During this semester, you will participate in a sustainability module designed to guide you in learning about and applying sustainability concepts and principles. While the course Teaching Assistant will serve as a facilitator, module sessions will be primarily student-driven and completed in groups. This means that students *must* take responsibility for their own learning processes. All directions and materials required to complete these activities will be provided in module workbooks on T-square. Prior to each session, students will be required to individually review the session workbook and complete all before-class activities. Most in-class activities will be completed in groups, so it is imperative that students complete individual before class assignments so that in-class activities go smoothly. In addition, many module activities will be completed in-class. Students should take advantage of this time so that assignments do not become burdensome outside of class. The final deliverable for the module is a "mini-project," which will help student groups in completing their course project. Module activities will count as the grade for Homework 1. The mini-project grade will also count toward the final project grade. See Session 0: Introduction to Sustainability Module for more details.

Week	Date	Class Session	Assignments[a]	Readings
1	**Aug 21**	Course introductions; Sustainability Module: Session 0 Module Introduction	1. In class: Student sustainability survey (part of HW 1 grade); 2. After class: Review Session 1 workbook and complete all before class activities 3. After class: Download Cmap Tools onto laptop	
	Aug 23	Sustainability Module: Session 1 Benchmarking Sustainability Knowledge using Concept Maps	1. **BRING LAPTOP TO CLASS** 2. In class: Submit all deliverables outlined in Session 1 workbook 3. After class: Review Session 2 workbook and complete all before class activities	
2	**Aug 28**	Sustainability Module: Session 2 Conceptualizing Sustainability through Peer Discussions	1. Be prepared to teach your sustainability theme 2. In class: Submit all deliverables outlined in Session 2 workbook 3. After class: Review Session 3 workbook and complete all before class activities	Course reader #11, 12, 13, 15, 14
	Aug 30	Sustainability Module: Session 3 Examining Sustainable Design through Evaluation of a Real World Project	1. Review BedZED case study 2. In class: Submit all deliverables outlined in Session 3 workbook 3. After class: Review Session 4 workbook and complete all before class activities	Course reader #1-10
3	**Sep 4**	Context sensitive solutions, Performance-based planning;	Project Selection and Team Contacts	#14
	Sep 6	Asset Management; Environmental and Social Impact Assessment		21, 20
4	**Sep 11**	Engineering Communication I: Written	Comm. Assignment 1 Out*	
	Sep 13	Sustainability Module: Session 4 Conducting Sustainability Analyses	1. In class: Submit all deliverables outlined in Session 4 workbook 2. After class: Finish mini-project 3. After class: Review Session 5 workbook and complete all before class activities	
5	**Sep 18**	Sustainability Module: Session 5 Showcasing Sustainability Knowledge Using Concept Maps	Comm. Assignment 1 Due* 1. **BRING LAPTOP TO CLASS** 2. Sustainability mini-project due 3. In class: Submit all deliverables outlined in Session 5 workbook	
	Sep 20	Quiz 1		
6	**Sep 25**	Optimization by Calculus		#16
	Sep 27	Optimization by Linear and Integer programming		#17
7	**Oct 2**	Incorporating Uncertainty in Systems Analysis	HW2 out	#19
	Oct 4	Engineering Communication	Comm. Assignment 2 Out*	

Week	Date	Class Session	Assignments[a]	Readings
8	Oct 9	Queuing Analysis	HW2 Due	#21, 18
	Oct 11	Intro to Engineering Economy: Time Value of Money	Comm. Assignment 2 Due Oct 12 DROP COURSE WITH "W" DEADLINE	Econ. Reader 1-22
9	Oct 16	NO CLASS FALL BREAK		
	Oct 18	Present Worth, Factor Tables, Effective Interest Rates; Equivalent	HW3 Out	Econ Reader 22-41
10	Oct 23	Uniform Annual Worth, Perpetuity		
	Oct 25	Arithmetic Gradient, Geometric Gradient	HW3Due	Econ Reader 41-58
11	Oct 30	Quiz 2		
	Nov 1	Project Evaluation: Net Present Value, IRR, Benefit/Cost Analysis;	HW4 out	Econ Reader 58-74
12	Nov 6	Engineering Communication III: Oral		
	Nov 8	Inflation, Depreciation, Spreadsheet Financial Tools	HW5 out, HW4 Due	Econ Reader 74-103
13	Nov 13	EE Practice		
	Nov 15	Ethics	HW5 Due	
14	Nov 20	Quiz 3		
	Nov 22	NO CLASS		
15	Nov 27	Project Presentations		
	Nov 29			
16	Dec 4	Project Presentations		
	Dec 6		Final Project Report & Peer Evaluations due	
17	Dec 10	FINAL EXAM		

[a]Note that assignments for the Sustainability Module are outlined in the workbook available on T-square. Only significant milestones are detailed in this course schedule.

* Final dates will depend on Dr. Rosenstein. The dates in this are only tentative.

Disclaimer

The instructors reserve the right to amend this syllabus as necessary. Any changes will be announced in class or via T-square announcement.

School of Civil & Environmental Engineering, Georgia Institute of Technology
Sustainable Engineering
CEE 4803B (86450) / CEE 8813B (83332)
1:35 to 2:55 pm T Th
Mason 298

1. Instructor and TA

John Crittenden
Civil & Environmental Engineering
Office: College of Management 4425
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Arka Pandit
Civil & Environmental Engineering
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2. Course Description

CEE 4803B / 8813B is an exploration of the methods necessary for designing and implementing changes in engineering to increase sustainability. This course will identify the impacts associated with resource consumption and environmental pollution, and present the quantitative tools necessary for assessing environmental impacts and to design for sustainability. The class will involve lectures, some by guest speakers, environmental field measurements, and a group project. The topics to be covered include: Industrial Ecology Earth Systems Engineering and Management Integration of the Environmental, Social and Economic Issues Life Cycle Assessment Material Flow Analysis

Engineering Working Definition of Sustainable Development:
Our socioeconomic system is far from sustainable and this may cause us guilt and perhaps frustration and so there may be a tendency to just give up. Consequently, we will use this definition for this class. Roy F. Weston: "Sustainable Development is a process of change in which the direction of investment, the orientation of technology, the allocation of resources, and the development and functioning of institutions that meet present needs and aspirations without endangering the capacity of natural systems to

absorb the effects of human activities, and without compromising the ability of future generations to meet their own needs and aspirations." A simpler definition which describes the target of sustainable engineering is: Sustainable Engineering is defined here *as the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment.*

These requirements reflect that social conditions, economic opportunity, and environmental quality are essential if we are to reconcile society's development goals with international environmental limitations.

3. Class Operation

This course involves active learning on the part of the students. The class will be broken up into groups. Each group will work together on homework and final project.

Prerequisites:
This course is meant to be taken **by both engineering and non-engineering students**. It requires basic mathematical skills, and the willingness to conduct quantitative analyses. Especially for the group project, students with different backgrounds may be called upon to contribute in different ways.

Attendance:
Students should sign in at the beginning of each class. A sign sheet will be provided by the instructor.

Grading:
Homework and Class Participation 40%
Mid-Term Exam 20%
Class Project 40%

Homework:
Homework is to be done individually (**except** HW2 on LCA cooperative learning) but you certainly can seek advice from your group and others.

Homework Assignments Format:
1. Unless the problems are very short, begin each problem on a new sheet.
2. Always restate the problem indicating the given information, desired information and explain your method. Make liberal use of comments.

3. Make liberal use of sketches.
4. Always use units in your calculations and on graphs. For quantitative problems please underline answers in red.
5. Above all, BE EXTREMELY NEAT.

Class Project:
Class Projects are to be worked on as a group. They represent a group effort and each group will write a group report. Sustainable solutions will require coordinated collective efforts with stakeholders with diverse opinions and objectives. The group projects should be considered an opportunity to explore this approach.

The report should not be unnecessarily long, but should contain the following elements:

Abstract. Most technical journals require abstracts which summarize the content of a paper in one or two paragraphs. The abstracts may be written in the form used in the scientific Journals. Please include concluding remarks in the abstract. Every statement in the conclusion should be capable of undergoing careful scrutiny.

Introduction. The introduction should provide the reader with a concise statement of the theoretical and rational basis. It would be appropriate to follow the form frequently used in the scientific Journals for the introduction and succeeding sections.

Approach. The approach that was used to gather, analyze and synthesize a solution to the issue should be discussed in this section. If this section is written correctly, the results and discussion section will be more concise and will focus only on the presentation of the results and interpret the results.

Results and Discussion. Results should be summarized, tabulated, or plotted neatly. Particular attention should be paid to the units employed. S.I. units are preferred. Sample calculations should be shown. This section of the report gives greatest insight into the integrity of the writers. It is very easy to over interpret results. Caution should be observed in interpreting the results and alternatives should be considered.

Future Research and/or Investigation. Most good investigations raise additional questions that cannot be addressed without additional time, talent and resources. The section should help focus the reader on what should be undertaken next.

References Cited. Please refer to the American Chemical Society guideline for the format that should be used and the manner in which references are cited (http://pubs.acs.org/userimages/ContentEditor/1246030496632/chapter14.pdf).

10 to 15 pages of text, excluding references, tables and figures, is a good target for the paper. I expect you to use the basic principles that we discuss in class: 12 green engineering principles in your recommendations, LCA, material flow analysis. Also, I expect you to examine sustainability metrics.

4. Course Content

Week	Date	Content	Remarks
1	8/24	Class Introduction / Sustainability and Sustainable Engineering	**Reading:** • McIsaac, G.F., Morey, N.C. Engineers' role in sustainable development: Considering cultural dynamics, *Journal of Professional Issues in Engineering Education and Practice* **1998**, *124* (4), 110-119 • Crittenden. J.C. Engineering the quality of life. *Clean Techn. Environ. Policy* **2002**, 4, 6-7. • Xu, M., et al. Gigaton Problems Need Gigaton Solutions, *Environ, Sci. Technol.* **2010**, *44* (11), 4037-4041. • Mihelcic, J.R., et al. Sustainability science and engineering: The emergence of a new metadiscipline. *Environ. Sci. Technol.* **2003**, *37* (23), 5314-5324. • Sustainability and Engineering in New Zealand: Practical Guidelines for Engineers.
	8/26	Energy and Climate Change	**Readings** • Chow, J., Kopp, R.J., Portney, P.R. Energy resources and global development. *Science* **2003**, *302*, 1528-1531. • Pacala, S., Socolow, R. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* **2004**, *305*, 968-972. • Washington, W.M., et al. How much climate change can be avoided by mitigation? *Geophys. Res. Lett.* **2009**, *36*, L08703.
2	8/31	Energy and Climate Change (Continue)	**HW1 Due on 8/31:** Terminology Essay **Reading:** • Matthews, E., et al. *The Weight of Nations: Material Outflows from Industrial Economies*; World Resource Institute: Washington DC, 2000. • Bringezu, S., et al. International comparison of resource use and its relation to economic growth: The development of total material requirement, direct material inputs and hidden flows and the structure of TMR. *Ecol. Econ.* **2004**, *51*, 97-124.
	9/2	Material Flow Analysis	
3	9/7	**Life Cycle Assessment: Cooperative Learning**	**HW2 Due on 9/7**: LCA Cooperative Learning (prepare before class and finish and submit the homework during class) **Reading:** • ISO. *Environmental Management: Life Cycle Assessment, Principles and Framework*; ANSI/ISO 14040, 1997. • Hendrickson, C., Horvath, A. Economic input-output models for environmental life-cycle assessment. *Environ. Sci. Technol.* **1998**, *32* (7), 184A-191A. • Williams, E.D., Ayers, R.U., Heller, M. The 1.7 kilogram microchip: Energy

	9/9	**Group project presentation**	and material use in the production of semiconductor devices. *Environ. Sci. Technol.* **2002**, *36* (24), 5504-5510. • Hauschild, M.Z. Assessing environmental impacts in a life-cycle perspective. *Environ. Sci. Technol.* **2005**, *39* (4), 81A-88A. • Scientific Applications International Corporation (SAIC). *Life Cycle Assessment: Principles and Practice*; US EPA: Cincinnati, Ohio, 2006. • Carnegie Mellon University Green Design Institute. *Economic Input-Output Life Cycle Assessment (EIO-LCA) Model*; http://www.eiolca.net/. • National Renewable Energy Laboratory (NREL). *U.S. Life-Cycle Inventory Database*; http://www.nrel.gov/lci/.
4	9/14	Life Cycle Assessment	**HW3 Due on 9/14**: MFA Practices **Reading:** • Duchin, F. Industrial input-output analysis: Implications for industrial ecology. *PNAS* **1992**, *89*, 851-855. • Lave, L.B., et al. Using input-output analysis to estimate economy-wide discharges. *Environ. Sci. Technol.* **1995**, *29* (9), 420A-426A. • Hendrickson, C.T.; Lave, L.B.; Matthews, H.S. *Environmental Life Cycle Assessment for Goods and Services, Chapter 2: Hybrid LCA Analysis*; Resources for the Future Press: Washington DC, 2006.
	9/16	LCA Example on Water Treatment Technologies	
5	9/21	Urban Sustainability: Introduction	**Reading:** • Grimm, N.B., et al. Global change and the ecology of cities. *Science* **2008**, *319*, 756-760. • Batty, M. The size, scale, and shape of cities. *Science* **2008**, *319*, 769-771. • Li, K., et al. Development of a framework for quantifying the environmental impacts of urban development and construction practices. *Environ. Sci. Technol.* **2007**, *41* (14), 5130-5136.
	9/23	Urban Sustainability: Urban Development Simulations (Case Study of Phoenix), Air Quality and Heat Island Simulations, Cyberinfrastructure for Urban Sustainability	
6	9/28	Grand Challenges continue. Technology Solutions	**HW4 Due on 9/28**: LCA Practices **Reading:** • Steffen, W., et al. *Global Change and the Earth System: A Planet under Pressure, Executive Summary*; Springer: Heidelberg, 2004. • Costanza, R., et al. Sustainability or collapse: What can we learn from integrating the history of humans and the rest of nature? *Ambio* **2007**, *36* (7), 522-527. • Liu, J., et al. Complexity of coupled human and natural systems. *Science* **2007**, *317*, 1513-1516. • Kolpin, D. W., et al. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999-2000: A national reconnaissance. *Environ. Sci. Technol.* **2002**, *36* (6): 1201-1211. • Allenby, B. The industrial ecology of emerging technologies. *J. Ind. Ecol.* **2009**, *13* (2), 168-183.
	9/30		

7	10/5	Risk Assessment: Target Plots, Pollution Prevention Assessment Framework, QSAR Model, Relative Risk Indices	**Reading:** • US EPA. *Pollution Prevention (P2) Framework*; 2005 • Cash, G.G. Prediction of chemical toxicity to aquatic organisms: ECOSAR vs. Microtox® Assay. *Environ. Toxicol. Water Qual.* **1998**, 13 (3), 211-216. http://www.epa.gov/oppt/exposure/pubs/episuite.htm
	10/7	**Exam:** Quantitative problems on LCA and MFA	
8	10/12	Risk Assessment: Comparison of Two Industry Sectors, Reaction Pathway Selection	
	10/14	Tools for Sustainable Engineering 12 Principles for Sustainable or Green Engineering	**Reading:** • Anastas, P.T., Zimmerman, J.B. Design through the 12 principles of green engineering. *Environ. Sci. Technol.* **2003**, *37* (5), 94A-101A. • McDonough, W., et al., Applying the principles of green engineering to cradle-to-cradle design. *Environ. Sci. Technol.* **2003**, *37* (23), 434A-441A. The President's Council on Sustainable Development. *Towards a Sustainable America;* 1999.
9	10/19	No Class: Student Recess	
	10/21	Legal and Political Realm of Sustainability, Business Model of Sustainability, Role of Engineers, Sustainability Metrics	
10	10/26	**Interim Group Project Presentation**	**HW5 Due on 10/26**: Thermodynamics and Target Plot 5 undergraduate groups
	10/28	**Interim Group Project Presentation**	4 graduate groups per class
11	11/2	Nanotechnology (Guest lecture by Dr. Yongsheng Chen)	**HW6 Due on 11/2:** Examples of Applying 12 principles of Green Engineering **Reading:** • TBD
	11/4	Global Perspectives	
12	11/9	Introduction to Industrial Ecology	**Reading:** • Thomas, V.M., Choi, D., Luo, D., Okwo, A., Wang, J.H. Relation of biofuel to bioelectricity and agriculture: Food security, fuel security, and reducing greenhouse emissions. *Chemical Engineering Research and Design* **2009**, in press.
	11/11	Biofuels (Guest lecture by Dr. Valerie Thomas)	
13	11/16	Metrics of Industrial Ecology: Thermodynamic Metrics and Environmental Metrics (Global Warming Potential)	**Reading:** • Jelinski, L.W., et al. Industrial ecology: Concepts and approaches. *PNAS* **1992**, *89*, 793-797. • Frosch, R.A. Industrial ecology: A philosophical introduction. *PNAS* **1992**, *89*, 800-803. • von Hauff, M., Wilderer, P.A. Industrial ecology: Engineered representation of sustainability. *Sustain. Sci.* **2008**, *3*, 103-115.
	11/18	Metrics of Industrial Ecology: Other Environmental Metrics	
14	11/23	No Class: Prepare for Project Presentation	

	11/25	No Class: Thanksgiving Holiday	
15	11/30	**Final Group Project Presentation**	3 groups per class
	12/2	**Final Group Project Presentation**	3 groups per class
16	12/7	**Final Group Project Presentation**	**HW7 Due on 12/7**: Comments on Sustainable Engineering and the Course
	12/9	No Class. Prepare for Project Report	**Project Report Due on 12/10, 5 pm**

3. Useful Links

UN website:
http://www.un.org/esa/sustdev/index.html (UN Division of Sustainable Development)
http://www.unep.org/ (UN Environment Programme)

Indicators
http://www.epa.gov/indicate/ (US EPA)
http://www.iisd.org/measure/ (International Institute for Sustainable Development)
http://themes.eea.eu.int/all_indicators_box (European Union)
http://themes.eea.eu.int/index_html#Sectors_and_activities (European Union)
www.sustainable-development.gov.uk/indicators/index.htm (United Kingdom)
http://www.epa.gov/iwi/ (Watersheds)
http://www.epa.gov/ost/biocriteria/index.html (Biocriteria)
http://www.worldbank.org/data/wdi2001/ (World Development Indicators)
http://www.met-office.gov.uk/research/hadleycentre/ (Climate Prediction & Research)

Construction
http://www.rethinkingconstruction.org/ (Constructing Excellence)
http://www.cbpp.org.uk/ (Best Practices)
http:www.m4i.org.uk (Movement for Innovation)
http://www.ciria.org.uk/ (Indicators)

Waste
http://www.epa.gov/osw/ (US EPA)
http://ewasteguide.info/ (Electronic Wastes)

http://www.epa.gov/p2/
http://www.epa.gov/oppt/p2framework/ (The P2 Program)
http://www.epa.gov/epaoswer/non-hw/reduce/epr/ (The Product Stewardship Program)

Sustainability-related Journals:
http://www3.interscience.wiley.com/journal/118902538/home (Journal of Industrial Ecology)
http://pubs.acs.org/journal/esthag (Environmental Science & Technology)
http://www.elsevier.com/locate/jclepro (Journal of Cleaner Production)
http://www.elsevier.com/locate/ecolecon (Ecological Economics)
http://www.elsevier.com/locate/energy (Energy)
http://www.elsevier.com/locate/enpol (Energy Policy)
http://www.elsevier.com/locate/jenvman (Journal of Environmental Management)
http://www.springerlink.com/content/100370 (Environmental Management)
http://www.springerlink.com/content/120154 (Sustainability Science)
http://www.elsevier.com/locate/resconrec (Resources, Conservation and Recycling)
http://www.scientificjournals.com/sj/lca/ (International Journal of Life Cycle Assessment)

Energy

http://www.esource.com/public/default.asp (Energy Business Intelligence)
http://www.eren.doe.gov/ (Renewable Energy)
http://www.cee1.org/home.html (Consortium of Energy Efficiency)

LCA

http://iac.rutgers.edu/database/ (14,000+ Assessment)
http://hpb-1a.nrel.gov/lci/ (US LCI database)
http://www.epa.gov/nrmrl/lcaccess/ (US EPA)
http://www.life-cycle.org/ (LCA Links)
http://www.eiolca.net/ (CMU EIOLCA)

Listing of World Wide Environmental Agencies / NGO's

http://www.worldbank.org/nipr/epas/index.htm (Listing of Agencies)
http://gemi.org/ (Global Environnemental Management Initiative)
http://www.sustainablebusiness.com/ (Sustainable Business)
http://www.wbcsd.org/ (World Business Council on Sustainable Development)
http://www.ceres.org/ (Coalition for Environmentally Responsible Economies)
http://www.globalreporting.org/ (Global Reporting Initiative)
http://www.ulsf.org/ (University Leaders for a Sustainable Future)
http://www.sdcn.org/ (Sustainable Development Communications Network)
http://www.environmentalsustainability.info/ (Environment Portal & Search Engine)
http://www.secondnature.org/ (Second Nature – Sustainable Education)
http://www.sustainableliving.org/ (Sustainable Living Network)
http://www.ucsusa.org/ (Union of Concerned Scientists)

http://www.epa.gov/oppt/greenengineering/ (The Green Engineering Program)
http://www.epa.gov/dfe/ (Designing for Environment Program)
http://www.epa.gov/cpg/ (Comprehensive Procurement Guidelines Program)
http://www.epa.gov/sectors/ (The Industry Partners Program)
http://www.epa.gov/epaoswer/hazwaste/minimize/

APPENDIX B

EXAMPLES OF STUDENT CONSIDERATION OF SUSTAINABLE DESIGN CRITERIA IN CAPSTONE DESIGN PROJECT REPORTS

To aid judges in identifying application of criteria in project reports, a set of examples for how the 16 criteria may be met in CEE projects was compiled. This phase was essential for elucidating what each criterion "looks like" in student projects. First, capstone design reports completed by GT CEE students in Fall 2010 were evaluated using the rubric, and instances of criteria consideration were recorded. Afterward, Fall 2007 projects were examined using the amended rubric and any new examples were recorded. This process was repeated for Fall 2004 and Fall 2001 projects. A comprehensive list summarizing how CEE students may incorporate sustainable design criteria into capstone projects was developed to supplement the rubric (Tables B.1 – B.4).

Table B.1. Example applications of environmental design criteria in capstone projects.

Environmental Design Criteria	Examples
Minimizes natural resource depletion (quantity)	• Collecting and using rainwater for non-consumption purposes (e.g. green roof to collect irrigation water). • Promoting use of non-fossil-fuel-based transportation (e.g. providing bike racks or other techniques that do not include using renewable energy sources). • Decreasing fossil fuel consumption by using local materials. • Limiting disturbed land area. • Reducing conversion of land area to impervious surfaces. • Maximize available flow rate from dam or through culvert. • Promoting water and/or energy efficiency practices (e.g. water efficient landscaping)
Prevents waste (material)	• Designing project to use as much of existing structures (roadways, buildings, etc.) as possible. • Minimizing material waste during construction. • Providing opportunities for users of a project to recycle. • Recycling materials from structures that cannot be rehabilitated. • Using recycled materials for design (e.g. building a roadway with recycled concrete)
Protects natural ecosystems (quality)	• Implementing erosion control measures to protect water quality and aquatic habitats. • Preventing release of pollutants into water sources. • Using vegetation to preserve water quality (e.g. use of green spaces, stream buffers, landscaping islands). • Choosing a site to minimize interference with ecosystems or ecosystems components (e.g. water sources, wetlands, trees, etc.) • Consideration of endangered species in design process. • Limiting disruption of stream floor, contours, or flow. • Minimizing overall impacts on natural environments.
Uses inherently safe and benign materials (to environment)[1]	• Use of natural building materials (e.g. compressed earth block) • Use of materials whose production as low environmental impacts (e.g. construction concrete and steel). • Use of rapidly-renewable plant materials (e.g. bamboo). • Use of certified environmentally-safe materials.
Uses renewable energy sources	• Incorporation of on-site renewable energy (wind, hydropower, solar, bio-based, geothermal) into design. • Use of renewable energy during construction. • Providing alternative fueling stations. • Providing preferred parking for alternative fuel vehicles.

[1]Use of standard civil engineering materials (e.g. wood, steel, etc.) is not sufficient to satisfy this criterion *unless* the report suggests that the group made a conscious decision about material choice based on environmental concerns.

Table B.2. Example applications of social design criteria in capstone projects.

Social Design Criteria	Examples
Addresses community and stakeholder requests	• Improvements to traffic congestion (e.g. minimizing queuing at traffic signals, improving level of service). • Sequencing construction to minimize impact on traffic flow. • Avoiding routing traffic through residential areas. • Including green spaces (or other features) to increase local property values. • Holding charettes or other community events to solicit local concerns and opinions about design project. • Incorporating concerns or suggestions voiced during charettes or other community events into design. • Improving access to public transportation. • Improving access to public amenities for pedestrians and bicyclists. • Increasing vehicular access to public amenities (e.g. more parking spaces) • Including accommodations for handicapped or elderly patrons (e.g. facilitating transport across steep hill using pedestrian bridge, adding extra handicapped parking spaces). • Providing recreational amenities. • Considering aesthetic appeal of designs. • Providing opportunities to enjoy scenic surroundings. • Choosing site to minimize disruption or acquisition of private property. • Promoting community atmosphere (e.g. building retail community rather than box shopping center)
Considers local circumstances and cultures	• Designing projects to blend in with the aesthetic qualities of the community. • Considering future needs of community (e.g. future population growth). • Preserving historical sites. • Honoring historical sites that must be altered during design (e.g. adding commemorative plaques). • Minimizing land excavation for sites that may have archeological value. • Providing designs that allow community to maintain small-town atmosphere. • Honoring community requests for LEED certification or environmental protection. • Considering local demographic during design.

Considers local circumstances and cultures	• Designing projects to blend in with the aesthetic qualities of the community. • Considering future needs of community (e.g. future population growth). • Preserving historical sites. • Honoring historical sites that must be altered during design (e.g. adding commemorative plaques). • Minimizing land excavation for sites that may have archeological value. • Providing designs that allow community to maintain small-town atmosphere. • Honoring community requests for LEED certification or environmental protection. • Considering local demographic during design.
Protects human health and well-being	• Addressing driver expectancy issues and/or minimizing driver confusion (e.g. with appropriate signs, signals, etc.). • Adding features to protect pedestrians (barriers to roadways, crosswalks, etc.). • Adding appropriate measures to prevent flooding (e.g. detention ponds, drainage improvements). • Providing appropriate amenities or access for fire rescue (e.g. water lines) or other safety services. • Compliance with laws, regulations, or codes (e.g. AASHTO). • Considering safety at any time during project life cycle (construction, use, etc.). • Adding retaining walls to stabilize slopes and promote safety. • Adding barriers and/or fences to prevent cars from leaving roadway. • Designing project with consideration of extreme events (e.g. designing for a 100 year storm, staying above 10 year flood plain, etc.). • Ensuring proper lighting for proper use of project. • Ensuring structural integrity of designs (e.g. controlling crack propagation, ensuring suitability of soil for construction). • Including methods for monitoring and/or improving indoor and outdoor air quality. • Minimizing entry of pollutants into buildings.
Uses inherently safe and benign materials (to humans)[1]	• Use of low emitting adhesives, sealants, paints, coatings, and/or flooring systems. • Use of low or non-toxic materials (e.g. non-carcinogens, non-irritants, etc). • Use of moisture-resistant materials that reduce biological contaminants. • Use of materials that require non-toxic cleaning procedures.

[1]Use of standard civil engineering materials (e.g. wood, steel, etc.) is not sufficient to satisfy this criterion *unless* the report suggests that the group made a conscious decision about material choice based on health concerns.

Table B.3. Example applications of sustainable engineering tools in capstone projects.

Sustainable Engineering Tool/Strategy	Example
Incorporates life cycle analysis	• Considering impacts of project over its lifecycle, rather than just its useful life. • Using results from a life cycle analysis. • Conducting a simplified life cycle analysis using a Materials, Energy, Toxicity (MET) matrix, Eco-Indicator 99, or other appropriate tool. • Defining the project lifecycle.
Incorporates environmental impact assessment tools	• Recommending that an environmental impact assessment be completed. • Using results from an environmental impact assessment.
Incorporates systems analysis	• Defining the project system by setting boundaries, defining system components and attributes, and explaining links between system components and attributes. • Determining project impacts (economic, environmental, social) within and outside of system boundaries.
Uses innovative technologies to achieve sustainability	• Developing a design that cannot be analyzed using traditional engineering software (e.g. diverging diamond interchange). • Applying new design/development paradigms (e.g. new urbanism). • Designing for LEED certification. • Using non-typical solutions for a geographical area (e.g. roundabouts uncommon in GA). • Using a sustainable design tool, such as a design abacus.

Table B.4. Example applications of economic design criteria in capstone projects.

Economic Design Criteria	Example
Considers economic impacts of executing environmental principle(s)	• Calculating costs for enacting an environmental sustainability principle. • Finding cost-effective methods for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit while enacting an environmental sustainability principle (e.g. charge extra for residential units located near green space). • Completing environmental sustainability principle to decrease costs (e.g. material, energy, and/or water efficiency). • Implementing environmental sustainability principle to receive tax break (e.g. LEED certification). • Comparing costs of design alternatives with different levels of environmental consideration/protection.
Considers economic impacts of executing social principle(s)	• Calculating costs for enacting a social sustainability principle (e.g. cost to improve safety, aesthetics, etc). • Finding cost-effective methods for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit from enacting a social sustainability principle (e.g. adding commercial space near residential areas to increase property values). • Maximizing social benefit, while minimizing costs (e.g. maximizing number of parking spaces while minimizing cost). • Increasing factor safety/margin of error to both ensure public safety and prevent expensive re-designs in the event of project failure.
Quantifies economic costs and benefits.	• Estimation of project costs. • Use of cost-benefit analyses.

APPENDIX C

STUDENT SUSTAINABILITY SURVEY

The Student Sustainability Survey was developed, administered, and analyzed to gain insights into students' interest in, knowledge of, and previous educational experiences related to sustainability. The survey was administered at the beginning and end of Fall 2011 and Spring 2012 capstone design courses, as well as before and after module implementation in two Fall 2012 sections of Civil Engineering Systems.

Student Sustainability Survey

Please answer the following questions designed to gain insight into your knowledge of, interest in, attitudes towards, and previous experiences related to sustainability.

1. Describe yourself by answering the following:

   A. Academic major:

   ___ Civil Engineering ___ Environmental Engineering ___ Other: _____________

   B. Gender:

   ___ Male ___ Female

   C. Country of origin:

   ___ United States ___ Other: ______________________________

   D. Academic Standing:

   ___ Freshman ___ Sophomore ___ Junior ___ Senior ___ Graduate

   E. Cumulative Georgia Tech grade point average (GPA): _______.

   F. Indicate your mother's highest level of education.

   ___ High school ___ Post-secondary other than college ___ Some college

   ___ College degree ___ Some graduate school ___ Graduate degree

   G. Indicate your father's highest level of education.

   ___ High school ___ Post-secondary other than college ___ Some college

   ___ College degree ___ Some graduate school ___ Graduate degree

Note: Subsequent survey items denoted with a "" were included on versions of this survey administered before and after module implementation in either Capstone Design (CEE 4090) and Civil Engineering Systems (CEE 3000). Other survey items were included on the Student Sustainability Survey only before module implementations.*

2. The statements below are related to sustainable development. Indicate how important you think it is for engineers to be able to complete the listed tasks. Also indicate how confident you are in your ability to complete the listed tasks*.

	A. How important do you think it is for engineers to be able to:							B. How confident are you in your ability to:						
	Not at all important			Neutral			Extremely	Not at all confident			Neutral			Extremely confident
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
A. Develop sustainable solutions to engineering problems.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
B. Discuss the concept of sustainable development.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
C. Discuss the connection between poverty, population, consumption, and environmental degradation.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
D. Discuss economic factors that affect sustainable development.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
E. Discuss environmental factors that affect sustainable development.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
F. Discuss social factors that affect sustainable development.	O	O	O	O	O	O	O	O	O	O	O	O	O	O
G. Evaluate an engineering design based on sustainability criteria.	O	O	O	O	O	O	O	O	O	O	O	O	O	O

3. The statements below are related to sustainable design. Indicate how important you think it is for engineers to be able to develop designs that meet the listed criteria. Also indicate how confident you are in your ability to develop designs that meet the listed criteria*.

	A. How important do you think it is for engineers to develop designs that meet the following criteria:							B. How confident are you in your ability to develop designs that meet the following criteria:						
	Not at all important			Neutral			Extremely	Not at all confident			Neutral			Extremely confident
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
A. Addresses community and stakeholder requests	O	O	O	O	O	O	O	O	O	O	O	O	O	O
B. Considers local circumstances and cultures	O	O	O	O	O	O	O	O	O	O	O	O	O	O
C. Incorporates life cycle analysis	O	O	O	O	O	O	O	O	O	O	O	O	O	O
D. Incorporates environmental impact assessment tools	O	O	O	O	O	O	O	O	O	O	O	O	O	O
E. Incorporates systems analysis	O	O	O	O	O	O	O	O	O	O	O	O	O	O
F. Uses innovative technologies to achieve sustainability	O	O	O	O	O	O	O	O	O	O	O	O	O	O
G. Minimizes natural resource depletion	O	O	O	O	O	O	O	O	O	O	O	O	O	O
H. Prevents waste	O	O	O	O	O	O	O	O	O	O	O	O	O	O
I. Protects natural ecosystems	O	O	O	O	O	O	O	O	O	O	O	O	O	O
J. Protects human health and well-being	O	O	O	O	O	O	O	O	O	O	O	O	O	O
K. Uses inherently safe and benign materials	O	O	O	O	O	O	O	O	O	O	O	O	O	O
L. Uses renewable energy sources	O	O	O	O	O	O	O	O	O	O	O	O	O	O

4. Indicate your level of interest in the following:

	Not at all interested 1	2	3	Neutral 4	5	6	Extremely Interested 7
A. Sustainable design	O	O	O	O	O	O	O
B. Sustainable development	O	O	O	O	O	O	O

5. Indicate your level of interest in the following topics:

	Not at all interested 1	2	3	Neutral 4	5	6	Extremely Interested 7	Do not know
A. Bioeconomy, biomaterials, and biorefineries	O	O	O	O	O	O	O	O
B. Clean/renewable energy and energy efficiency	O	O	O	O	O	O	O	O
C. Climate change	O	O	O	O	O	O	O	O
D. Conservation, biodiversity and ecosystems services	O	O	O	O	O	O	O	O
E. Corporate responsibility and sustainability	O	O	O	O	O	O	O	O
F. Environment and international development	O	O	O	O	O	O	O	O
G. Environmental economics	O	O	O	O	O	O	O	O
H. Environmental justice	O	O	O	O	O	O	O	O
I. Environmental law	O	O	O	O	O	O	O	O
J. Environmental policy	O	O	O	O	O	O	O	O
K. Environmental security	O	O	O	O	O	O	O	O
L. Food security	O	O	O	O	O	O	O	O
M. Global governance and sustainability	O	O	O	O	O	O	O	O
N. Globalization and international trade	O	O	O	O	O	O	O	O
O. Green buildings	O	O	O	O	O	O	O	O
P. Human nutrition, health and environment	O	O	O	O	O	O	O	O
Q. Natural resources management	O	O	O	O	O	O	O	O
R. Pollution and environmental health	O	O	O	O	O	O	O	O
S. Poverty alleviation and development	O	O	O	O	O	O	O	O
T. Spirituality, links to science and sustainability	O	O	O	O	O	O	O	O
U. Sustainable cities	O	O	O	O	O	O	O	O
V. Sustainable community development	O	O	O	O	O	O	O	O
W. Sustainable infrastructure (water, waste, energy)	O	O	O	O	O	O	O	O
X. Sustainable transportation	O	O	O	O	O	O	O	O

6. Indicate the extent to which you have learned about sustainable development through:

	Not at all 1	2	3	Neutral 4	5	6	To a great extent 7	Have not participated in activity
A. CEE courses at Georgia Tech.	O	O	O	O	O	O	O	O
B. Non-CEE courses (engineering and non-engineering) at Georgia Tech.	O	O	O	O	O	O	O	O
C. Participating in clubs and organizations at Georgia Tech.	O	O	O	O	O	O	O	O
D. Participating in non-academic activities.	O	O	O	O	O	O	O	O
E. Participating in undergraduate research at Georgia Tech.	O	O	O	O	O	O	O	O
F. Reading, listening to, or watching media sources (e.g. newspapers, magazines, news, educational television, radio, etc).	O	O	O	O	O	O	O	O
G. Participating in an internship or cooperative education experience.	O	O	O	O	O	O	O	O

7. Rate the quality of sustainability education in your home department at Georgia Tech.

__ Excellent __ Very Good __ Average __ Marginal __ Poor

8. Reflecting on your curricula, indicate how important is it for your home department to improve sustainability education by:

	Not at all important 1	2	3	Neutral 4	5	6	Extremely important 7
A. Adding more sustainability concepts into existing classes.	O	O	O	O	O	O	O
B. Offering more courses that focus on sustainability concepts and issues.	O	O	O	O	O	O	O
C. Providing more guidance on how to apply sustainability concepts to design.	O	O	O	O	O	O	O
D. Providing more opportunities for students to discuss sustainability topics.	O	O	O	O	O	O	O

9. Describe how you would improve sustainability education in your home department at Georgia Tech.

____

____

____

10. Indicate the extent to which your interest in sustainability affects the following:

	Not at all			Neutral			To a great extent
	1	2	3	4	5	6	7
A. Your choice of academic major	O	O	O	O	O	O	O
B. Your future career goals	O	O	O	O	O	O	O

11. Indicate the extent to which you agree or disagree with the following statements:

	Strongly Disagree			Neutral			Strongly Agree
	1	2	3	4	5	6	7
A. Current trends in environmental degradation are sustainable.	O	O	O	O	O	O	O
B. Current trends in population growth are sustainable.	O	O	O	O	O	O	O
C. Current trends in resource consumption are sustainable.	O	O	O	O	O	O	O
D. Sustainable development can improve global conditions.	O	O	O	O	O	O	O
E. Sustainable development is economically practical.	O	O	O	O	O	O	O

12. Indicate the extent to which you agree or disagree with the following statements:

	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
	1	2	3	4	5
A. We are approaching the limit of the number of people the earth can support.	O	O	O	O	O
B. Humans have the right to modify the natural environment to suit their needs.	O	O	O	O	O
C. When humans interfere with nature, it often produces disastrous consequences.	O	O	O	O	O
D. Human ingenuity will ensure that we do NOT make the earth unlivable.	O	O	O	O	O
E. Humans are severely abusing the environment.	O	O	O	O	O
F. The earth has plenty of natural resources if we just learn how to develop them.	O	O	O	O	O
G. Plants and animals have as much right as humans to exist.	O	O	O	O	O
H. The balance of nature is strong enough to cope with the impacts of modern industrial nations.	O	O	O	O	O
I. Despite our special abilities humans are still subject to the laws of nature.	O	O	O	O	O
J. Human destruction of the natural environment has been greatly exaggerated.	O	O	O	O	O
K. The earth has only limited room and resources.	O	O	O	O	O
L. Humans were meant to rule over the rest of nature.	O	O	O	O	O
M. The balance of nature is very delicate and easily upset.	O	O	O	O	O
N. Humans will eventually learn enough about how nature works to be able to control it.	O	O	O	O	O
O. If things continue on their present course, we will soon experience a major ecological disaster.	O	O	O	O	O

13. ABET is the board responsible for accrediting engineering programs in the United States. Listed below are ten student outcomes defined by ABET. Indicate how important you think it is for engineers to be able to demonstrate the listed outcomes. Also indicate how confident you are in your ability to demonstrate the listed outcomes*.

	A. How important do you think it is for engineers to be able to:							B. How confident are you in your ability to:						
	Not at all important			Neutral			Extremely important	Not at all confident			Neutral			Extremely confident
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
A. Apply knowledge of mathematics, science, and engineering	O	O	O	O	O	O	O	O	O	O	O	O	O	O
B. Design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	O	O	O	O	O	O	O	O	O	O	O	O	O	O
C. Function on multidisciplinary teams	O	O	O	O	O	O	O	O	O	O	O	O	O	O
D. Identify, formulate, and solve engineering problems	O	O	O	O	O	O	O	O	O	O	O	O	O	O
E. Understand professional and ethical responsibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O
F. Communicate effectively	O	O	O	O	O	O	O	O	O	O	O	O	O	O
G. Understand the impact of engineering solutions in a global, economic, environmental, and societal context	O	O	O	O	O	O	O	O	O	O	O	O	O	O
H. Engage in life-long learning	O	O	O	O	O	O	O	O	O	O	O	O	O	O
I. Demonstrate a knowledge of contemporary issues	O	O	O	O	O	O	O	O	O	O	O	O	O	O
J. Use the techniques, skills, and modern engineering tools necessary for engineering practice.	O	O	O	O	O	O	O	O	O	O	O	O	O	O

APPENDIX D

STUDENT CURRICULUM SURVEY

The Student Curriculum Survey was developed to gain insight into student perceptions of undergraduate sustainability education. The survey prompts students to use a seven-point scale to rank the extent of coverage of each of the STAUNCH® sustainability topics by their CEE courses. In addition, students are prompted to list up to five CEE courses that extensively addressed sustainability. The survey was administered to students at the end of the Spring 2012 Capstone Design course.

Student Curriculum Survey

1. Think about all the courses you have taken in civil and environmental engineering (CEE). Which courses do you believe addressed sustainability? Rank the top 5 courses which addressed sustainability, with #1 being the course that most addressed the topic. You do not have to fill in all five spaces.

   1. ______________________________
   2. ______________________________
   3. ______________________________
   4. ______________________________

2. To what extent were the following **economic concepts** discussed or applied in your CEE classes?

	Not at all			Neutral			To a great extent	I don't know
	1	2	3	4	5	6	7	
A. Gross National Product (GNP)/productivity/profitability	O	O	O	O	O	O	O	O
B. Resource use/exhaustion (materials, energy, water)	O	O	O	O	O	O	O	O
C. Finances	O	O	O	O	O	O	O	O
D. Production/consumption patterns	O	O	O	O	O	O	O	O
E. Developmental economics	O	O	O	O	O	O	O	O
F. Markets/commerce/trade	O	O	O	O	O	O	O	O
G. Accountability	O	O	O	O	O	O	O	O

3. To what extent were the following **environmental concepts** discussed or applied in your CEE classes?

	Not at all			Neutral			To a great extent	I don't know
	1	2	3	4	5	6	7	
A. Policy/administration	O	O	O	O	O	O	O	O
B. Products and services: transportation, eco-products, and/or life cycle analysis	O	O	O	O	O	O	O	O
C. Pollution, accumulation of toxic waste, and/or effluents	O	O	O	O	O	O	O	O
D. Biodiversity	O	O	O	O	O	O	O	O
E. Resource efficiency, eco-efficiency, and/or cleaner production	O	O	O	O	O	O	O	O
F. Climate change: global warming, air emissions, and/or ozone depletion	O	O	O	O	O	O	O	O
G. Resources use: depletion and/or conservation of materials, energy, and/or water	O	O	O	O	O	O	O	O
H. Land use: desertification, deforestation, erosion, and/or soil depletion	O	O	O	O	O	O	O	O
I. Alternatives: energy, designs, and/or technologies	O	O	O	O	O	O	O	O

4. To what extent were the following **social concepts** discussed or applied in your CEE classes?

	Not at all			Neutral			To a great extent	I don't know
	1	2	3	4	5	6	7	
A. Demography/population	O	O	O	O	O	O	O	O
B. Employment/unemployment	O	O	O	O	O	O	O	O
C. Poverty	O	O	O	O	O	O	O	O
D. Bribery and/or corruption	O	O	O	O	O	O	O	O
E. Equity and/or justice	O	O	O	O	O	O	O	O
F. Health	O	O	O	O	O	O	O	O
G. Politics	O	O	O	O	O	O	O	O
H. Education and training	O	O	O	O	O	O	O	O
I. Diversity and social cohesion	O	O	O	O	O	O	O	O
J. Culture and/or religion	O	O	O	O	O	O	O	O
K. Labor and/or human rights	O	O	O	O	O	O	O	O
L. Peace and security	O	O	O	O	O	O	O	O
M. Work and life balance	O	O	O	O	O	O	O	O

5. To what extent were the following **multi-dimensional concepts** discussed or applied in your CEE classes?

	Not at all			Neutral			To a great extent	I don't know
	1	2	3	4	5	6	7	
A. People as part of nature and/or limits to growth	O	O	O	O	O	O	O	O
B. Systems thinking and applications	O	O	O	O	O	O	O	O
C. Responsibility	O	O	O	O	O	O	O	O
D. Governance	O	O	O	O	O	O	O	O
E. Holistic thinking	O	O	O	O	O	O	O	O
F. Long-term thinking	O	O	O	O	O	O	O	O
G. Communication and reporting	O	O	O	O	O	O	O	O
H. Sustainable development	O	O	O	O	O	O	O	O
I. Ethics and philosophy	O	O	O	O	O	O	O	O
J. Transparency (in design and/or decision-making processes)	O	O	O	O	O	O	O	O

6. To what extent were the following sustainable design principles discussed or applied in your CEE classes?

	Not at all			Neutral			To a great extent	I don't know
	1	2	3	4	5	6	7	
A. Address community and stakeholder requests	O	O	O	O	O	O	O	O
B. Consider local circumstances and cultures	O	O	O	O	O	O	O	O
C. Incorporate life cycle analysis	O	O	O	O	O	O	O	O
D. Incorporate environmental impact assessment tools	O	O	O	O	O	O	O	O
E. Incorporate systems analysis	O	O	O	O	O	O	O	O
F. Innovate and invent technologies to achieve sustainability	O	O	O	O	O	O	O	O
G. Minimize natural resource depletion	O	O	O	O	O	O	O	O
H. Prevent waste	O	O	O	O	O	O	O	O
I. Protect natural ecosystems	O	O	O	O	O	O	O	O
J. Protect human health and well-being	O	O	O	O	O	O	O	O
K. Use inherently safe and benign materials	O	O	O	O	O	O	O	O
L. Use renewable energy sources	O	O	O	O	O	O	O	O

APPENDIX E

SUSTAINABILITY MODULE EVALUATION MATERIALS

(CAPSTONE DESIGN)

To gain insights into students' perceptions of the sustainability module, those participating in capstone implementations were asked to provide feedback. At the end of some sessions, students were asked to provide open-ended reflections. Upon completion of the module, students completed the Module Evaluation Survey.

Session 2 Reflection Questions

Capstone students answered the following questions after participating in Session 2 where they learned about sustainability concepts through peer lectures.

1. Based on what you learned in Session 2: Student Sustainability Lectures, why is it important for engineers to learn about sustainability?

2. Describe any concepts or tools that you learned about that can be applied to your capstone project.

3. How did Session 2 go? Smoothly? Problems? You may also provide suggestions for improving the session.

Session 3 Reflection Questions

Capstone students answered the following questions after participating in Session 3 where they analyzed the Beddington Zero Energy Development Case Study.

1. Why is it important to investigate sustainability initiatives across the globe?

2. Describe any interesting strategies you learned about that you can apply to your capstone project.

3. How did Session 3 go? Smoothly? Problems? You may also provide suggestions for improving the session.

Module Evaluation Survey

Capstone students answered the following questions after participating in the entire sustainability module.

1. Reflect on the sustainability module you completed this semester during capstone design. Determine the extent to which you agree or disagree with the following statements.

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participating in the sustainability module helped me learn about sustainability concepts.	O	O	O	O	O	O	O
B. Participating in the sustainability module helped me learn about sustainable design.	O	O	O	O	O	O	O
C. I enjoyed participating in the sustainability module.	O	O	O	O	O	O	O
D. I will strive to engage in sustainable design as a practicing engineer.	O	O	O	O	O	O	O

APPENDIX F

SUSTAINABILITY MODULE EVALUATION MATERIALS (CORNERSTONE DESIGN)

To gain insights into students' perceptions of the sustainability module, those participating in cornerstone implementations were asked to provide feedback. At the end of individual sessions, students were asked to provide reflections. Upon completion of the module, students completed the Module Evaluation Survey.

Session 1 Reflection Questions

Cornerstone students answered the following questions after participating in Session 1 where they summarized their prior sustainability knowledge in a concept map.

1. Why is it especially important to use cross-links in developing a sustainability-related cmap?

   ____

   ____

2. Describe any concepts or tools that you have learned.

   ____

   ____

3. How did Session 1 go? Smoothly? Problems? You may also provide suggestions for improving the session.

   ____

   ____

4. To what extent do you agree or disagree with the following statements?

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participation in Session 1 helped me to examine the breadth of concepts I understand related to sustainability.	O	O	O	O	O	O	O
B. Participation in Session 1 helped me to examine the depth of my sustainability knowledge.	O	O	O	O	O	O	O
C. Participation in Session 1 helped me to examine the interrelated nature of my sustainability knowledge.	O	O	O	O	O	O	O
D. I enjoyed participating in Session 1.	O	O	O	O	O	O	O
E. I would recommend Session 1 to be implemented in future CEE 3000 courses.	O	O	O	O	O	O	O

Session 2 Reflection Questions

Cornerstone students answered the following questions after participating in Session 2 where they learned about sustainability concepts through peer discussions or peer lectures.

1. Based on what you learned in Session 2, why is it important for engineers to learn about sustainability?

   ____

   ____

2. Describe any concepts or tools that you learned.

   ____

   ____

3. How did Session 2 go? Smoothly? Problems? You may also provide suggestions for improving the session.

   ____

   ____

4. To what extent do you agree or disagree with the following statements?

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participation in Session 2 broadened my understanding of sustainability.	O	O	O	O	O	O	O
B. Participation in Session 2 deepened my understanding of sustainability.	O	O	O	O	O	O	O
C. Participation in Session 2 reinforced the complex and interrelated nature of the sustainability dimensions.	O	O	O	O	O	O	O
D. I enjoyed participating in Session 2.	O	O	O	O	O	O	O
E. I would recommend Session 2 to be implemented in future CEE 3000 courses.	O	O	O	O	O	O	O

Session 3 Reflection Questions

Cornerstone students answered the following questions after participating in Session 3 where they analyzed the Beddington Zero Energy Development Project.

1. Why is it important to investigate sustainability initiatives across the globe?

____

____

2. Describe any concepts or tools that you learned.

____

____

3. How did Session 3 go? Smoothly? Problems? You may also provide suggestions for improving the session.

____

____

4. To what extent do you agree or disagree with the following statements?

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participation in Session 3 improved my ability to analyze the impacts of a project on the economic, environmental, and social systems.	O	O	O	O	O	O	O
B. Participation in Session 3 improved my ability to assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	O	O	O	O	O	O	O
C. I enjoyed participating in Session 3.	O	O	O	O	O	O	O
D. I would recommend Session 3 to be implemented in future CEE 3000 courses.	O	O	O	O	O	O	O

Session 4 Reflection Questions

Cornerstone students answered the following questions after participating in Session 4 where they completed a preliminary sustainability analysis of an existing civil infrastructure system.

1. Why is it important to incorporate sustainability considerations during the design phase of a project?

   ____

   ____

2. Describe any concepts or tools that you applied to your capstone project.

   ____

   ____

3. How did Session 4 go? Smoothly? Problems? You may also provide suggestions for improving the session.

   ____

   ____

4. To what extent do you agree or disagree with the following statements?

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participation in Session 4 improved my ability to analyze the impacts of a project on the economic, environmental, and social systems.	O	O	O	O	O	O	O
B. Participation in Session 4 improved my ability to assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	O	O	O	O	O	O	O
C. I enjoyed participating in Session 4.	O	O	O	O	O	O	O
D. I would recommend Session 4 to be implemented in future CEE 3000 courses.	O	O	O	O	O	O	O

Session 5 Reflection Questions

Cornerstone students answered the following questions after participating in Session 5 where they summarized what they learned about sustainability in a concept map.

1. Why is it especially important to use cross-links in developing a sustainability-related cmap?

   ____

2. Describe any new concepts or tools that you learned about.

   ____

3. How did Session 5 go? Smoothly? Problems? You may also provide suggestions for improving the session.

   ____

4. To what extent do you agree or disagree with the following statements?

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participation in Session 5 helped me to examine the breadth of concepts I understand related to sustainability.	O	O	O	O	O	O	O
B. Participation in Session 5 helped me to examine the depth of my sustainability knowledge.	O	O	O	O	O	O	O
C. Participation in Session 5 helped me to examine the interrelated nature of my sustainability knowledge.	O	O	O	O	O	O	O
D. I can tell that my Session 5 concept map has improved, as compared to my Session 1 concept map.	O	O	O	O	O	O	O
E. I enjoyed participating in Session 5.	O	O	O	O	O	O	O
F. I would recommend Session 5 to be implemented in future CEE 3000 courses.	O	O	O	O	O	O	O

Module Evaluation Survey

Cornerstone students answered the following questions after participating in the entire sustainability module.

1. Reflect on the sustainability module you completed this semester. Determine the extent to which you agree or disagree with the following statements.

	Strongly Disagree			Neither Agree nor Disagree			Strongly Agree
	1	2	3	4	5	6	7
A. Participating in the sustainability module helped me learn about sustainability concepts.	O	O	O	O	O	O	O
B. Participating in the sustainability module helped me learn about sustainable design.	O	O	O	O	O	O	O
C. I enjoyed participating in the sustainability module.	O	O	O	O	O	O	O
D. I will strive to engage in sustainable design as a practicing engineer.	O	O	O	O	O	O	O

2. List any suggestions for improving the sustainability module.

____

____

____

____

APPENDIX G

STAUNCH® Report

Sustainability Tool for Assessing Universities Curricula Holistically (STAUNCH®) is software that was developed to determine the quality of a curriculum based on sustainability content. Rodrigo Lozano, the creator of STAUNCH® conducted an analysis of CEE courses using the tool. The full report is included below.

Organisational Sustainability

STAUNCH®
Assessment of Curricula Contribution to Sustainability at Georgia Institute of Technology

BSc in Civil Engineering and BSc in Environmental Engineering

Dr. Rodrigo Lozano
20th November 2011

Introduction

This report presents the results from the STAUNCH® assessment of the curricula of the BSc Civil Engineering and BSc Environmental Engineering at Georgia Institute of Technology for the year 2010-2011. The analysis was performed according to the information provided in the module descriptors (code, title, tutor, degree, year, route, number of credits, number of students, and aim or description).[1] For the number of students the information was taken from the academic year 2009-2010. The data was assessed against a four level scale (where the lowest grade indicates no contribution, and the highest excellent contribution) against the forty criteria presented in Table 1.

Table 1 STAUNCH® Module Sustainability Assessment Criteria

Economic	Environmental	Social
• GNP/Productivity/ Profitability • Resource use/exhaustion (materials, energy, water) • Finances • Production/ consumption patterns • Developmental economics • Markets/commerce/ trade • Accountability	• Policy/Administration • Products and services: transport, eco-products and services, LCA • Pollution/Accumulation of toxic waste/Effluents • Biodiversity • Resource efficiency/eco-efficiency/cleaner production • Climate change: Global warming/Emissions/Acid rain/Ozone depletion • Resources use: depletion and conservation of materials, energy, water • Desertification, deforestation, land use: erosion, soil depletion • Alternatives: energy, technologies	• Demography/Population • Employment/ Unemployment • Poverty • Bribery/corruption • Equity/Justice • Health • Politics • Education and training • Diversity and social cohesion • Culture and religion • Labour/Human rights • Peace and security • Work/life balance
Cross-cutting themes		
• People as part of nature/Limits to growth • Systems thinking/application • Responsibility • Governance • Holistic thinking • Long term thinking • Communication/Reporting • SD statement • Disciplinarity • Ethics/Philosophy • Transparency		

[1] The STAUNCH® assessment does not address the delivery of the modules, which may contribute considerably more to SD than what is written in the module descriptor.

During the assessment, the following assumption was made: Disciplinarity was graded when a module was offered to other schools (since all modules analysed are offered to both programmes their disciplinary approach is too similar). The two key indicators in the assessment are contribution, and strength. The contribution indicator provides information about breadth and depth with respect to SD, considering the balance of the economic, environmental, and social dimensions, along with the cross-cutting themes. Table 2 provides an illustration of this, as well as the qualitative level. Table 3 presents the module strength qualification. The Report first presents a Summary of the results, followed by the detailed results for each faculty, and finally the conclusions and recommendations.

Table 2 SD Contribution and qualitative levels

Hypothetical degree	Contribution	Level
LU001	0.00	None
LU101	0.01 - 0.67	Very low
LU201	0.67 - 1.29	Low
LU301	1.30 - 1.99	Medium
LU401	2.00 - 3.50	High
LU501	>3.50	Very high

Table 3 Module strength and its qualitative levels

Hypothetical degree	Strength	Level
LU1001	0.00	None
LU101	1.00 - 1.29	Low
LU201	1.30 - 1.49	Medium
LU301	1.50 - 1.99	High
LU401	>2.00	Very High

Summary of results

As indicated two bachelors were assessed: BSc Civil Engineering and BSc Environmental Engineering. Forty-four modules were analysed, all offered to both bachelors, from which 27 contribute to SD (61%). Their contributions and the strength are medium. The main focus of the faculty is on the environmental dimension, followed by the cross-cutting themes. There is limited focus on the social dimension and the economic dimensions. Of the overall 8,998 students[2], 58% are exposed to SD issues. Table 4 presents the summary of the results from both Bachelor programmes.

[2] The accumulated number of students refers to the total number of students attending all the modules.

The modules analysed were

Code	Title
CEE 1770	Intro to Engr Graphics
CEE 2040	Dynamics
CEE 2300	Environmental Engineering Principles
CEE 3000	Civil Engineering Systems
CEE 3010	Geomatics
CEE 3020	Civil Engineering Materials
CEE 3040	Fluid Mechanics
CEE 3055	Structural Analysis
CEE 3340	Environmental Engineering Laboratory
CEE 3770	Statistics and Applications
CEE 4090	Capstone Design
CEE 4100	Construction Engineering and Management
CEE 4101	Construction Seminar
CEE 4120	Construction Operations
CEE 4200	Hydraulic Engineering
CEE 4210	Hydrology
CEE 4225	Introduction to Coastal Engineering
CEE 4300	Environmental Engineering Systems
CEE 4310	Water Quality Engineering
CEE 4320	Hazardous Substance Engineering
CEE 4330	Air Pollution Engineering
CEE 4395	Environmental Systems Design
CEE 4405	Geotechnical Engineering
CEE 4510	Structural Steel Design
CEE 4520	Reinforced Concrete Design
CEE 4530	Timber and Masonry Design
CEE 4540	Infrastructure Rehabilitation
CEE 4550	Structural Analysis II
CEE 4600	Transportation Planning, Operations, and Design
CEE 4620	Environmental Impact Assessment
CEE 4640	Freeway/Interchange Planning and Design
CEE 4650	Site Development Planning/Design in Transportation
CEE 4791	Mechanical Behavior of Composites
CEE 4793	Composite Materials and Processes
CEE 4801B	Marine and Hydrokinetic Renewable Energy
CEE 4801R	Engineering as a Profession
CEE 4801RK	Engineering Alliance Seminar
CEE 4801RP	GTS 2000 Seminar
CEE 4802A	E-Stadium
CEE 4803	Construction Safety and Health
CEE 4803A	Transit System Planning and Design
CEE 4803B	Sustainable Engineering
CEE 4803C	Applied Geotechnique
CEE 4803D	Project Planning and Monitoring

Two modules can be considered to be good examples in their balance and contribution to SD: CEE 4100 Construction Engineering and Management (3.33), and CEE 4395 Environmental Systems Design (2.00).

Table 4 Summary of the faculty results

	%				% of modules contributing to SD	Contribution	Strength	% Students exposed	Accumulated Totals*
	Economic	Env.	Social	Cross-cutting					
BSc Civil Engineering	12%	62%	2%	24%	61%	1.36	1.35	57.75%	4,499
BSc Environmental Engineering	12%	62%	2%	24%	61%	1.36	1.35	57.75%	4,499
Civil and Environmental Engineering	12%	62%	2%	24%	61%	1.36	1.35	57.75%	8,998

* *i.e.* number of students in all modules

Results

The analysis shows the following key findings (for details refer to Table 5, Figure 2, Figure 3, Figure 4, and Figure 5 in the Appendix):

- From 88 modules analysed, 54 have a contribution to SD (with a weighted average of 61%), see Figure 1
- The contributions are medium (1.36), see Figure 1
- The weighted average strength of the Bachelor Programme is medium (weighted average of 1.39) with 71% overall graded with a 1, 19% with a 2, and 10% with a 3
- The main focus in the programmes is on the environmental dimension, with a weighted average of 61.87%
- The cross-cutting themes has an average of 23.57% (mainly through modules offered to other schools)
- The economic dimension has an average of 12.34%
- The social dimension is the least addressed, with 2.2%
- The accumulated number of students attending modules in the school is 8,998,of which 57.75% are exposed to SD issues

Of the 88 modules that contribute to SD:

- The contribution to the economic dimension is medium
- 54 contribute mainly to the environmental dimension
- The contribution to the social dimension is medium
- The contribution to the cross-cutting themes is low

Although most programmes contribute to the environmental dimension, the following contribute to other dimensions:

- CEE 4100 Construction Engineering and Management (40% in economic, 20% in environmental, 20% in social, and 20% in cross-cutting themes)
- CEE 4120 Construction Operations (50% in economic, and 50% in environmental)
- CEE 4395 Environmental Systems Design (33% in economic, environmental, and cross-cutting themes)
- CEE 4540 Infrastructure Rehabilitation (50% in economic, and 50% crosscutting themes)
- CEE4903B Sustainable Engineering (8% in economic, 46% in environmental, 8% in social, and 38% in cross-cutting themes)

Figure 6 shows that within the economic dimension the issues most addressed are: Finances (56%), Resource use/exhaustion (materials, energy, water) (33%), and Production/consumption patterns (11%). The following issues are not being addressed: GNP/productivity/profitability, Markets/commerce/trade, and Accountability.

Figure 7 shows that within the environmental dimension the issues most addressed are: Resource use: depletion and conservation of materials, energy, water (22%), Pollution/accumulation of toxic waste/effluents (17%), Products and services (mainly in regard to transport) (14%), and Desertification, deforestation, land use: erosion, soil depletion (14%). The following issue is not being addressed: Resource efficiency/ecoefficiency/cleaner production.

Figure 8 shows that within the social dimension the main issues addressed are: Employment/Unemployment (34%), Equity/Justice (33%), and Health (33%). Within the social dimension the following issues are not addressed: emography/Population, Poverty, Bribery/corruption, Politics, Education and training, Diversity and social cohesion, Culture and religion, Labour/human rights, Peace and security, and Work/life balance.

Figure 9 shows that within the cross-cutting themes the main issues addressed are: Disciplinarity (45%) (From courses taught at other schools, and SD statement (22%). The following issues are not being addressed: People as part of nature/limits to growth, Responsibility, Governance, Communication/reporting, Ethics/philosophy, and Transparency.

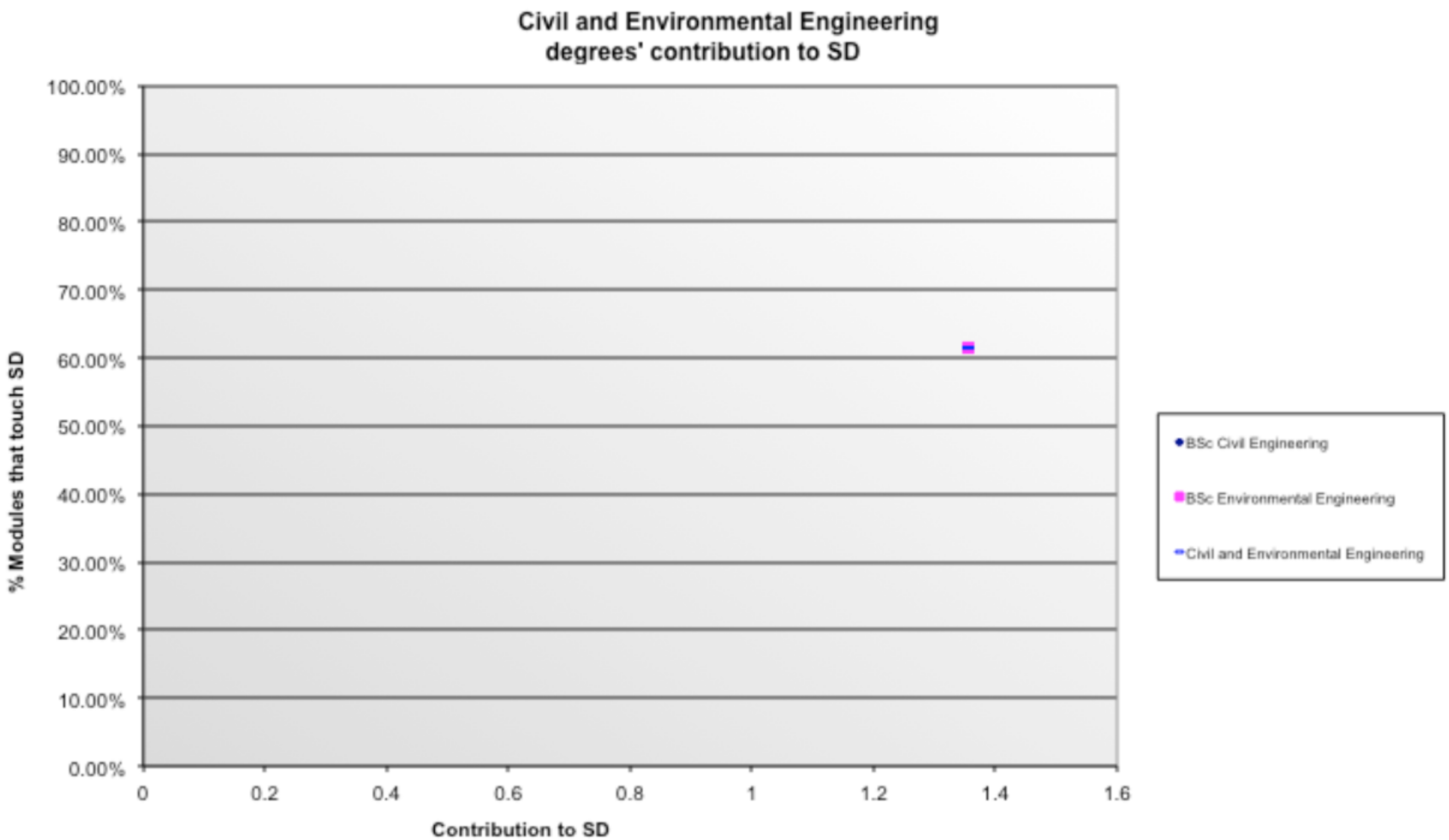

Figure 1 Civil and Environmental Engineering contribution to SD versus percentage of modules related to SD

Conclusions and recommendations

The STAUNCH® assessment of 88 module descriptors (44 modules are offered to both Bachelor Programmes) shows that the Civil and Environmental Engineering School has a strong focus on the environmental dimension. There are opportunities for improvement in the social and economic dimensions. Such as: GNP/productivity/profitability, Markets/commerce/trade, and Accountability, Demography/Population, Poverty, Bribery/corruption, Politics, Education and training, Diversity and social cohesion, Culture and religion, Labour/human rights, Peace and security, and Work/life balance.

The contribution and strength of the modules is reasonable. The percentage of students exposed to sustainability issues and the percentage of modules contributing to sustainability is good. Given these strictures, the school could consider addressing sustainability in its broader sense, i.e. going beyond environmental sustainability.

Four modules can be considered as good examples in their balance and contribution to SD: CEE 4100 Construction Engineering and Management (3.33), and CEE 4395 Environmental Systems Design (2.00).

The aim of the STAUNCH® assessment is to provide a picture of how both faculties are addressing SD issues. This allows an overview of how the students are being taught and prepared for their future careers in regards to their contribution to SD. The purpose of the assessment is not to create SD module or programme clones, but to facilitate disciplinary excellence whilst considering how teaching and decision-making (in each module, programme, and discipline) contributes to SD.

The school should consider discussing with other schools how to better incorporate economic and social issues in their curricula. Anent this, the assessment of the Civil and Environmental Engineering School could serve as an incentive for the other schools in the Georgia Institute of Technology to undertake an assessment of how their curricula contribute to sustainability.

The school (and the other schools?) should also consider identifying individuals within the teaching staff who are interested in SD and offer them the opportunity to engage in an SD 'Educate the Educators' programme, which could expand their knowledge of the topic. This should also be incorporated into other efforts and activities in the university, such as research, operations, outreach, planning, and management.

Appendices

Civil and Environmental Engineering Results

Table 5 Civil and Environmental Engineering programmes detailed results

	%				Total modules	% of modules of total	% of modules contributing to SD	Frequency %			Contribution	Strength	Students exposed (accumulated)	% students exposed of total in faculty	Total students
	Economic	Environmental	Social	Cross-cutting				F1	F2	F3					
BSc Civil Engineering	12.34%	61.87%	2.22%	23.57%	44	50%	61.36%	71.43%	18.57%	10.00%	1.36	1.39	2598	57.75%	4499
BSc Environmental Engineering	12.34%	61.87%	2.22%	23.57%	44	50%	61.36%	71.43%	18.57%	10.00%	1.36	1.39	2598	57.75%	4499
Civil and Environmental Engineering	12.34%	61.87%	2.22%	23.57%	44	50%	61.36%	71.43%	18.57%	10.00%	1.36	1.39	5196	57.75%	8998

Table 6 Civil and Environmental Engineering modules detailed results

Code	Title	Year	Credits	# of students	Module contribution	Economic	Environ mental	Social	Cross-cutting themes
CEE 1770	Intro to Engr Graphics	1	3	267	0.6667	0%	0%	0%	100%
CEE 2040	Dynamics	2	2	221		0%	0%	0%	0%
CEE 2300	Environmental Engineering Principles	2	3	313	0.6667	0%	100%	0%	0%
CEE 3000	Civil Engineering Systems	3	3	324	2.0000	14%	14%	0%	71%
CEE 3010	Geomatics	3	3	126		0%	0%	0%	0%
CEE 3020	Civil Engineering Materials	3	3	207		0%	0%	0%	0%
CEE 3040	Fluid Mechanics	3	3	249		0%	0%	0%	0%
CEE 3055	Structural Analysis	3	3	225		0%	0%	0%	0%
CEE 3340	Environmental Engineering Laboratory	3	3	25	0.6667	0%	100%	0%	0%
CEE 3770	Statistics and Applications	3	3	153	1.0000	0%	40%	0%	60%
CEE 4090	Capstone Design	4	3	225	1.0000	0%	75%	0%	25%
CEE 4100	Construction Engineering and Management	4	3	272	3.3333	40%	20%	20%	20%
CEE 4101	Construction Seminar	4	1	126		0%	0%	0%	0%
CEE 4120	Construction Operations	4	3	63	1.0000	50%	50%	0%	0%
CEE 4200	Hydraulic Engineering	4	3	115		0%	0%	0%	0%
CEE 4210	Hydrology	4	3	87	0.6667	0%	100%	0%	0%
CEE 4225	Introduction to Coastal Engineering	4	3	31	0.6667	0%	100%	0%	0%
CEE 4300	Environmental Engineering Systems	4	3	117	1.0000	0%	75%	0%	25%
CEE 4310	Water Quality Engineering	4	3	45	0.6667	0%	100%	0%	0%
CEE 4320	Hazardous Substance Engineering	4	3	35	0.8571	0%	83%	17%	0%
CEE 4330	Air Pollution Engineering	4	3	29	0.6667	0%	100%	0%	0%
CEE 4395	Environmental Systems Design	4	3	21	2.0000	33%	33%	0%	33%
CEE 4405	Geotechnical Engineering	4	3	175	0.6667	0%	100%	0%	0%
CEE 4510	Structural Steel Design	4	3	164		0%	0%	0%	0%
CEE 4520	Reinforced Concrete Design	4	3	133		0%	0%	0%	0%
CEE 4530	Timber and Masonry Design	4	3	56		0%	0%	0%	0%
CEE 4540	Infrastructure Rehabilitation	4	3	52	1.0000	50%	0%	0%	50%
CEE 4550	Structural Analysis II	4	3	77		0%	0%	0%	0%
CEE 4600	Transportation Planning, Operations, and Design	4	3	163	0.6667	0%	100%	0%	0%
CEE 4620	Environmental Impact Assessment	4	3	49	0.6667	0%	100%	0%	0%

Table 6 Civil and Environmental Engineering modules detailed results (cont.)

CEE 4640	Freeway/Interchange Planning and Design	4	3	40	0.6667	0%	100%	0%	0%
CEE 4650	Site Development Planning/Design in Transportation	4	3	19	0.6667	0%	100%	0%	0%
CEE 4791	Mechanical Behaviour of Composites	4	3	6	0.6667	0%	0%	0%	100%
CEE 4793	Composite Materials and Processes	4	3	2	0.6667	0%	0%	0%	100%
CEE 4801B	Marine and Hydrokinetic Renewable Energy	4	1	5	0.6667	0%	100%	0%	0%
CEE 4801R	Engineering as a Profession	4	1	55		0%	0%	0%	0%
CEE 4801RK	Engineering Alliance Seminar	4	1	39		0%	0%	0%	0%
CEE 4801RP	GTS 2000 Seminar	4	1	43	0.6667	100%	0%	0%	0%
CEE 4802A	E-Stadium	4	2	2		0%	0%	0%	0%
CEE 4803	Construction Safety and Health	4	3	35		0%	0%	0%	0%
CEE 4803A	Transit System Planning and Design	4	3	43		0%	0%	0%	0%
CEE 4803B	Sustainable Engineering	4	3	13	1.4444	8%	46%	8%	38%
CEE 4803C	Applied Geotechnique	4	3	19	0.6667	0%	100%	0%	0%
CEE 4803D	Project Planning and Monitoring	4	3	28		0%	0%	0%	0%

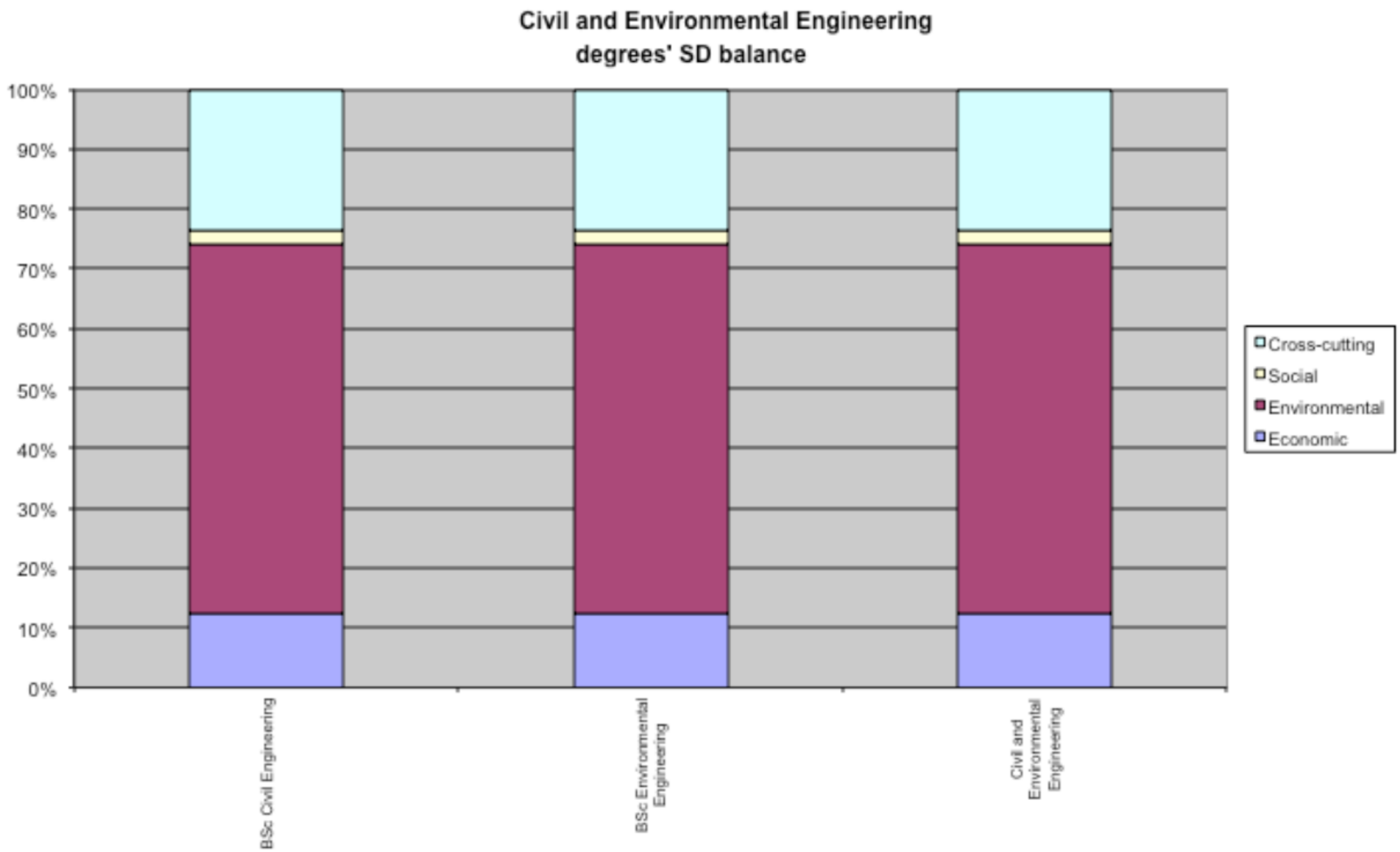

Figure 2 Civil and Environmental Engineering SD balance

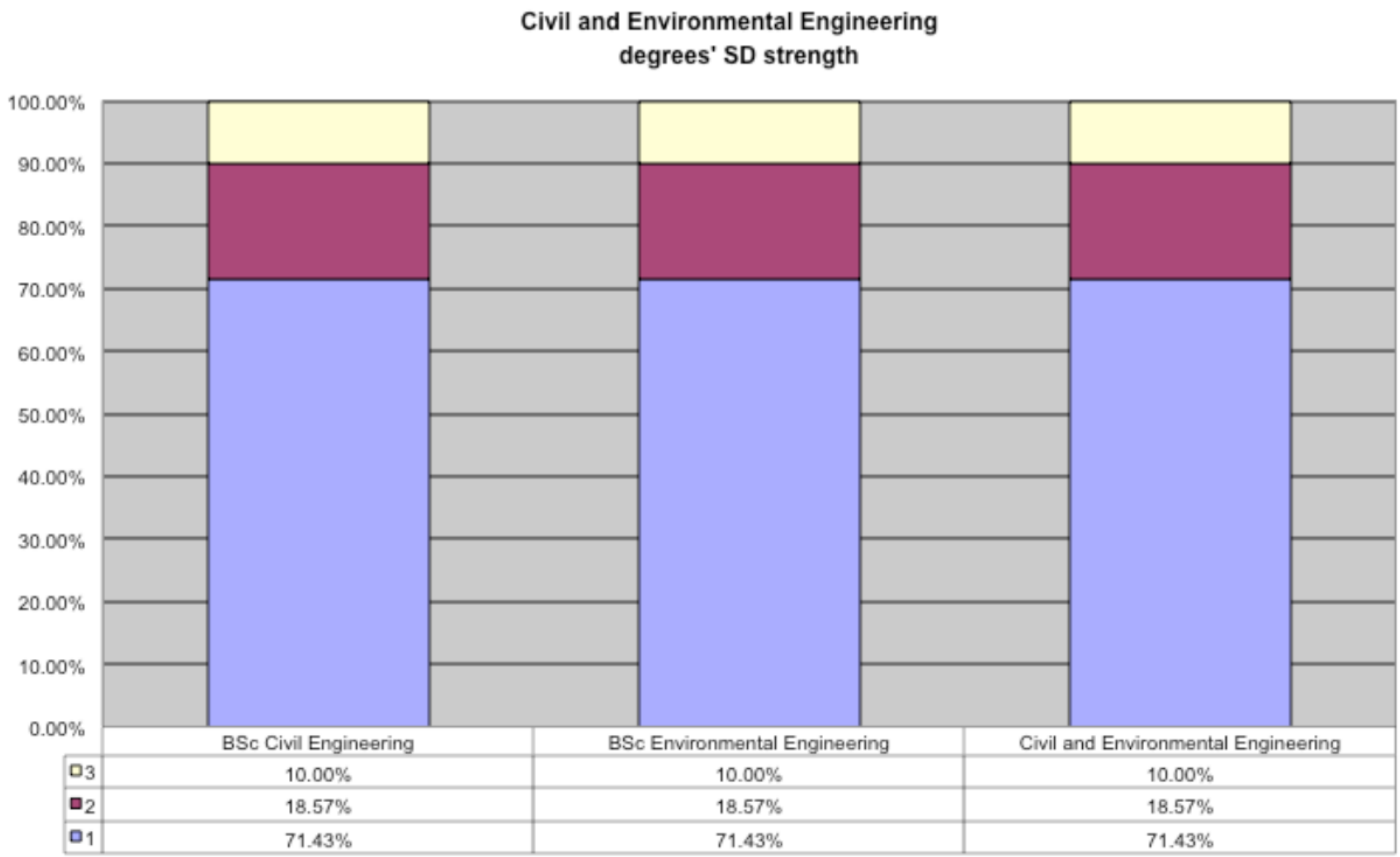

Figure 3 Civil and Environmental Engineering SD strength

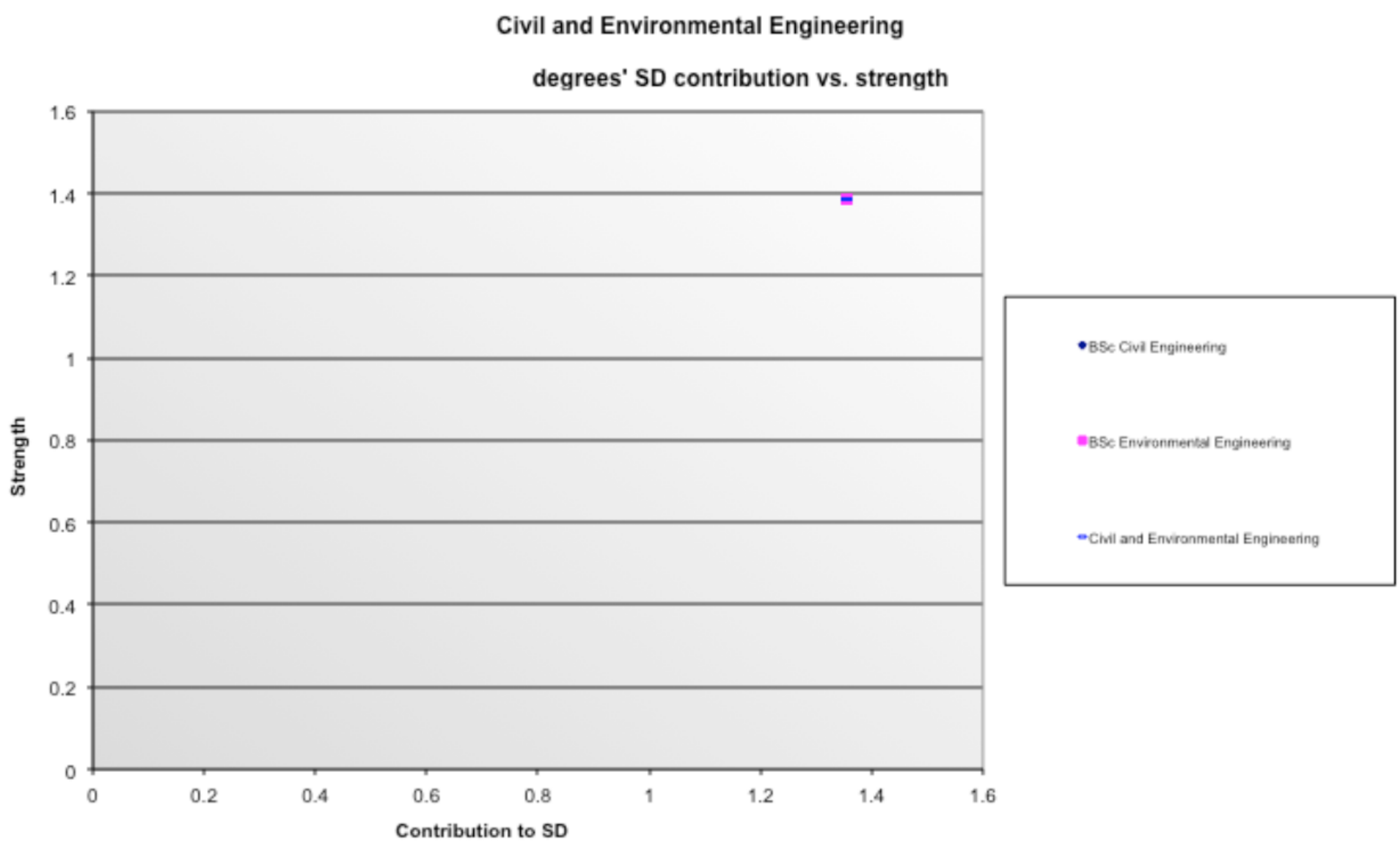

Figure 4 Civil and Environmental Engineering SD contribution versus strength

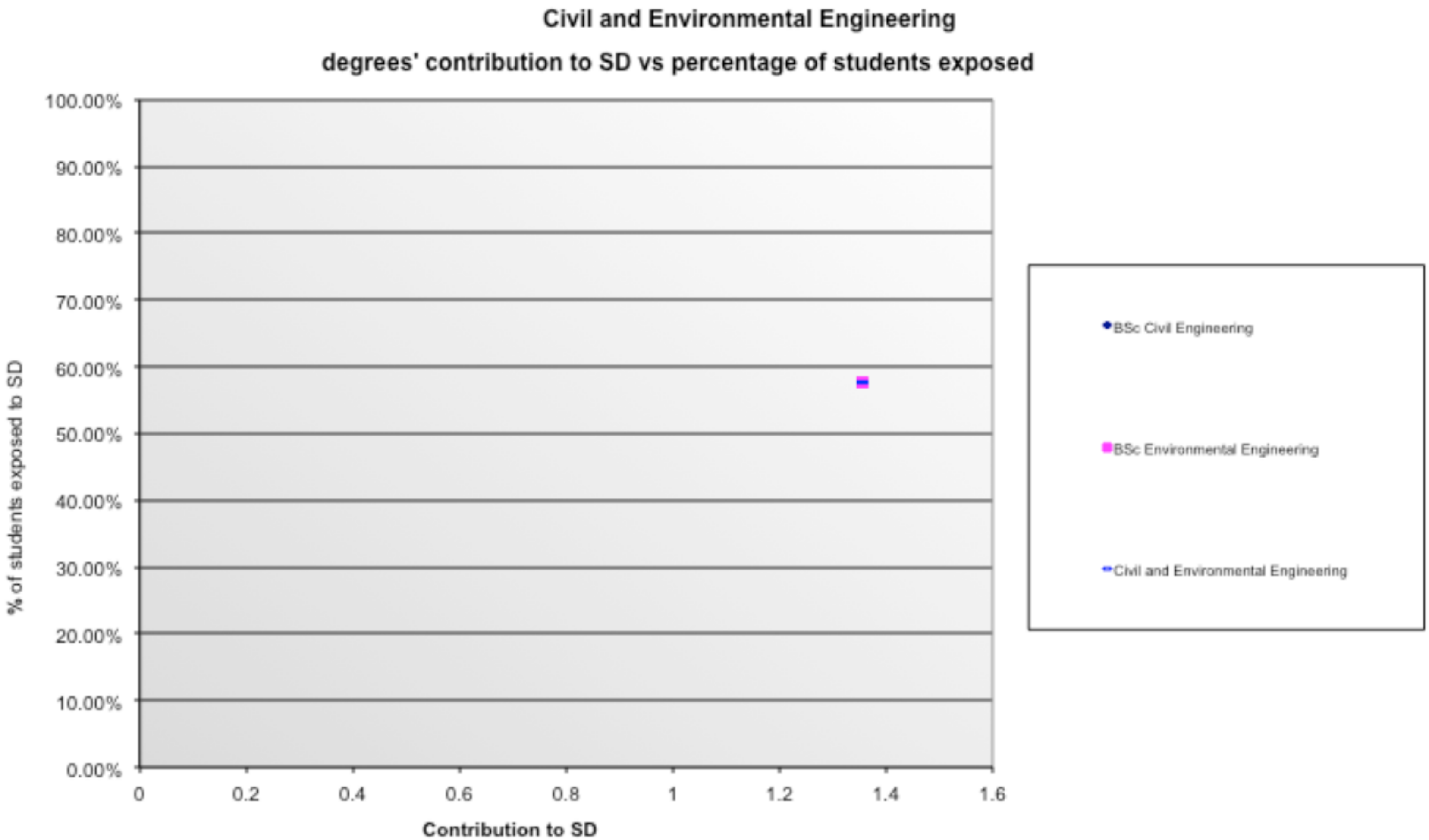

Figure 5 Civil and Environmental Engineering SD contribution vs. percentage of students exposed

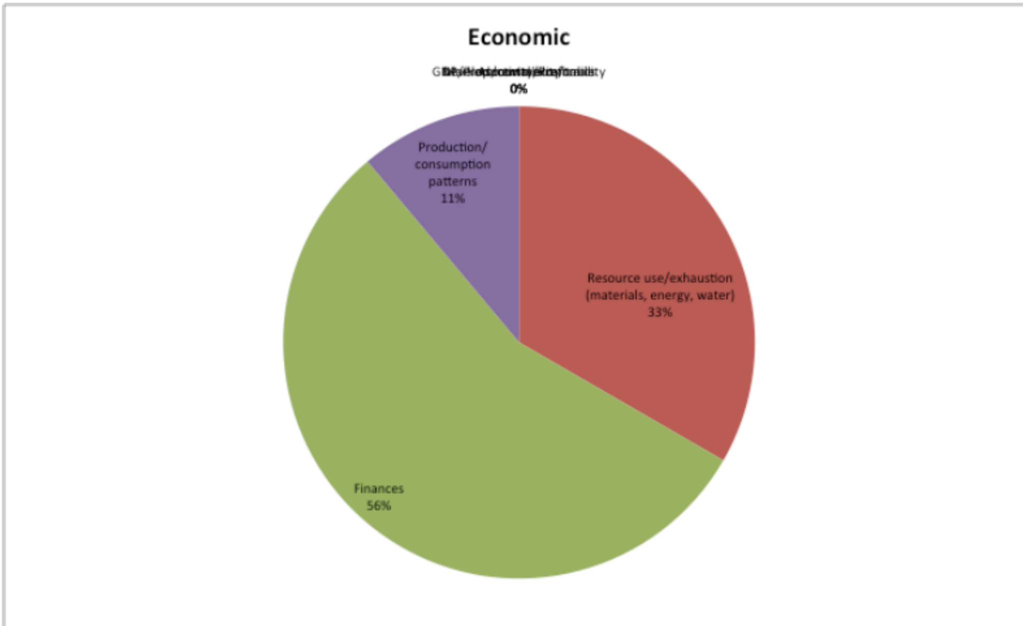

Figure 6 Civil and Environmental Engineering contribution to the economic dimension

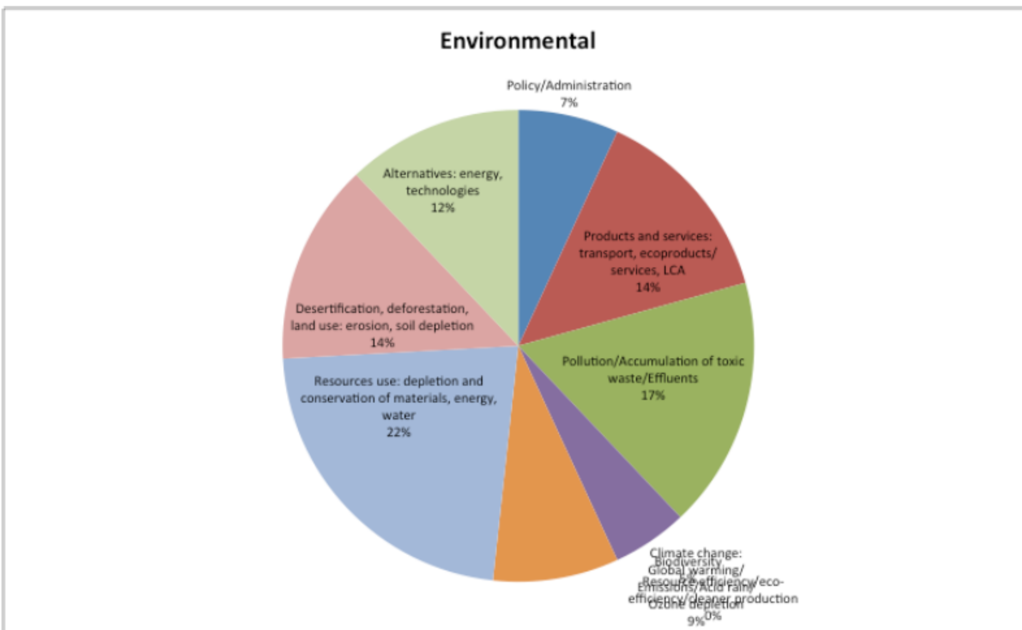

Figure 7 Civil and Environmental Engineering contribution to the environmental dimension

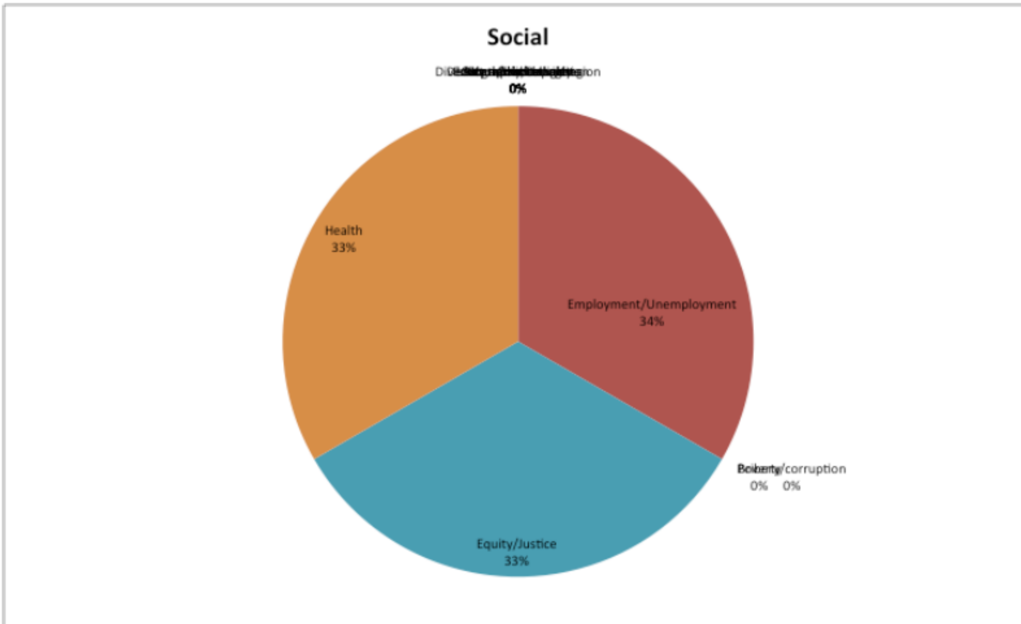

Figure 8 Civil and Environmental Engineering contribution to the social dimension

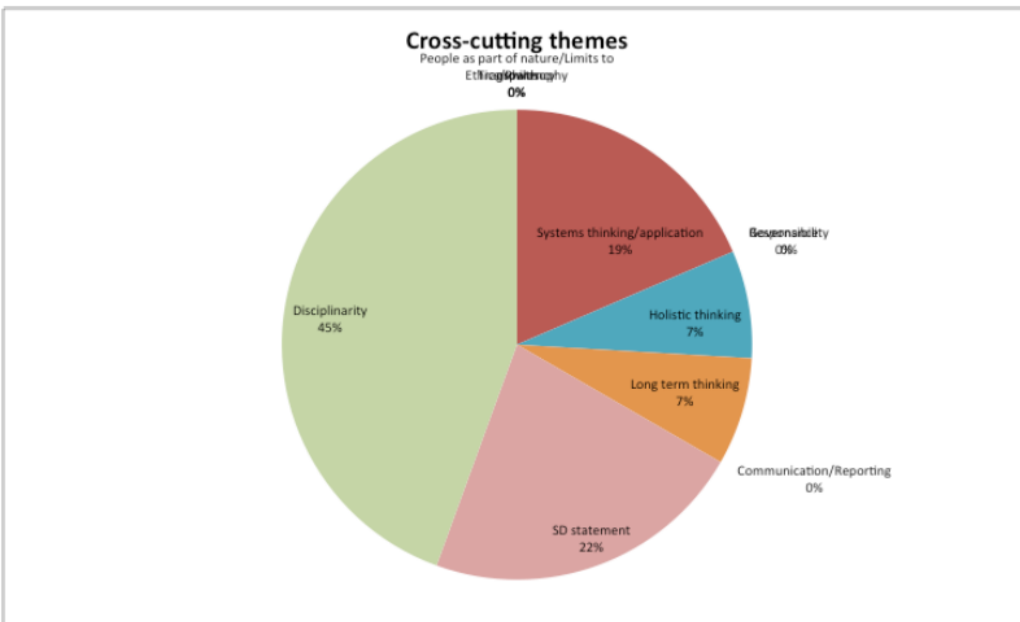

Figure 9 Civil and Environmental Engineering contribution to the cross-cutting themes

About Organisational Sustainability

Organisational Sustainability is dedicated to helping organisations plan changes to incorporate and institutionalise Sustainability into their strategic management, systems, and culture.

We do this by raising awareness and knowledge about sustainability, assessing where the organisation is, and orchestrating changes to help them become more sustainability orientated. Our expertise ranges from technical issues in Sustainable Development (such as air conditioning systems, indoor air quality, and chemical processes) to holistic and systematic assessment and reporting (for entire systems, but also in-depth for their elements), and to orchestrating organisational change (such as drivers, barriers to change, strategies to overcome them, institutional framework, leadership, and champions).

Our main areas of expertise include:

Sustainable Development: We consider Sustainability to address a dynamic and simultaneous Two-Tiered Sustainability Equilibria (TTSE): The first between the economic, environmental and social aspects; and the second between the temporal aspects, i.e. the short-, long- and longer-term perspectives.

Corporate Sustainability: We address the dynamic interactions among the economic, environmental, and social impacts, and interactions in the short, medium and long-term. We strive to achieve this through ethical, transparent, responsible, and accountable CS incorporation into operations, the institutional framework and strategies, decision-making, voluntary practices, and company culture.

Sustainability in Higher Education: We acknowledge that the future leaders, decision-makers, and intellectuals are moulded and shaped within the world's higher education institutions. Sustainability therefore needs to be embedded as the 'Golden Thread' in a university's Institutional Framework and systems.

Sustainability Reporting: We use a combination of narrative assessments and indicator-based assessment in our work. We have developed several tools to assess and report sustainability performance.

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APPENDIX H

SUSTAINABILITY MODULE FOR CAPSTONE DESIGN COURSE

A five-part sustainability module was implemented in the Spring 2012 section of Capstone Design. The learning-cycle-based module was developed using insights gained from assessments of the CEE curriculum and student sustainability knowledge. The instructor guide for implementing the capstone design version of the sustainability module is included below.

Learning About and Applying Sustainability Concepts and Principles in Design:

Instructor Guide

Spring 2012

Introduction to the Sustainability Module

Research Study

A research study is being conducted to determine the effects of Civil and Environmental Engineering (CEE) curricula at Georgia Tech on student ability to apply sustainability concepts during engineering design. Students enrolled in CEE 4090 will be asked to participate in a sustainability module designed to teach them about several sustainability topics that are pertinent to engineers. Several of the assignments completed during this module will be analyzed for research purposes, but no identifying information about students (i.e. name) will ever be disclosed. While module assignments are a required part of CEE 4090 and will be counted toward the final grade, student participation in this research study is voluntary. This means that students may elect to not have their assignments used in the research study. Students should contact Mary Katherine Watson (mwatson8@mail.gatech.edu) if they do not want to participate in this study.

Importance of Sustainability in Capstone Design

Although technological innovation may have contributed to current unsustainable practices, engineering is important for developing and implementing sustainable development strategies. In fact, most critical decisions related to sustainability, such as cost, appearance, materials selection, innovation, performance, environmental impact, and perceptions of quality, are made during the design process [1]. As engineering students that are about to enter the workforce, CEE 4090 students must be ready to integrate sustainability considerations during design. After all, they will be making the decisions that will impact the sustainability of our future infrastructure.

Module Overview

The goal of this module is to guide students in learning about and applying sustainability concepts and principles during design. During the module, capstone groups will self-navigate through several before-class and in-class activities to learn about sustainability and sustainable design. All materials needed for this module are found in the Sustainability Module Workbook and the course website. The module includes five class sessions:

- Session 1: Benchmarking Sustainability Knowledge Using Concept Maps
- Session 2: Conceptualizing Sustainability through Peer Lectures
- Session 3: Examining Sustainable Design by Evaluating a Real-World Project
- Session 4: Integrating Sustainability Considerations into your Capstone Design Project
- Session 5: Showcasing Sustainability Knowledge Using Concept Maps

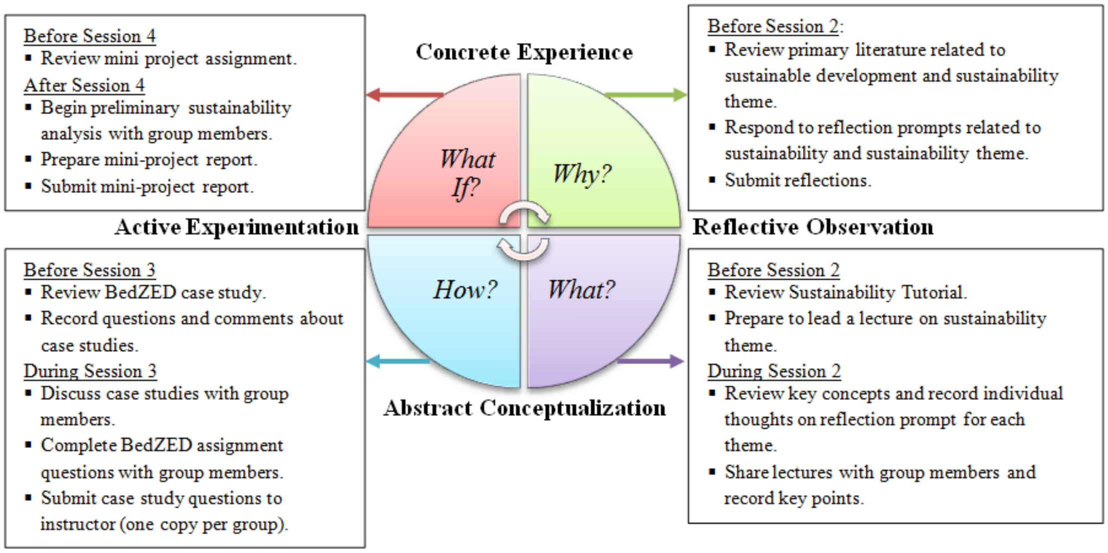
Module Learning Objectives

After completion of this five-part sustainability module, each student should be able to:

1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.
2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.
3. Analyze the impacts of a project on the economic, environmental, and social systems.
4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.

Module Design

This sustainability module is intentionally designed to improve student knowledge and application of sustainability by guiding them through a complete learning cycle. It is believed that complete learning occurs when students engage in all phases of the learning cycle, which includes concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE). Learning begins when a student engages in a given experience (CE) and continues as he or she reflects on that experience (RO). Student reflection leads to development of logical conclusions, to which theoretical or expert ideas can be added (AC). Finally, students test new concepts and skills (AE) to serve as templates for new experiences (CE). Each of the sessions was carefully developed to encourage students to complete each phase of the learning cycle [2-4].



Sequence of class activities based on learning cycle.

Session Layout

To help ensure that the module goes smoothly, each session will be organized in the same manner.

1. At the beginning of class, students will complete a minute paper exercise to demonstrate completion of the before-class assignments. In almost all cases, students will truly be given only one minute to respond to the prompt. Responses will be submitted after one minute is up.
2. The instructor will provide a brief overview of the session.
3. Students will complete the major activity for the session. All activities will be completed in capstone design groups, with the exceptions of sessions 1 and 5.
4. Students will complete an exercise to reflect on the session.
5. Students will submit in class assignments to the instructor or online.

Time Requirements

Students are responsible for completing assignments both before and during each module class. Most before-class exercises will be completed individually, while most in-class assignments will be completed in capstone project groups. It is important that students complete before-class assignments because they help their groups to complete in-class assignments. Before-class and in-class exercises are expected to take 3.5 and 9 hours to complete, respectively. It is critical that students use the time provided in class so that module activities do not become overwhelming.

Session No.	Class Description	Time Required Before Class* (hr)	Time Required During Class* (hr)
1	Concept Mapping	0.5	1
2	Student-Led Sustainability Lectures	1.5	3
3	Sustainability Case Study	1	2
4	Sustainability Mini Project	0.5	3

*Estimated.

Grading

Students will earn an overall grade for completion of module activities that will be included in their final class grade. A summary of all assignments and associated points is provided below.

Assignment	Due Date	Submission	Points
Session 1: Concept Mapping			
Preliminary Student Sustainability Survey	Before Session 1	Online	5
Minute paper	In Session 1	Paper	5
Practice cmap	In Session 1	Online	5
Sustainability cmap	In Session 1	Online	20
Session 1 Reflection Handout	In Session 1	Paper	5
Session 2			
Sustainability reflection	Before Session 2	Online	5
Sustainability theme reflection	Before Session 2	Online	5
Minute paper	In Session 2	Paper	5
Session 2 Activity Handout	In Session 2	Paper	20
Session 2 Reflection Handout	In Session 2	Paper	5
Session 3			
Minute Paper	In Session 3	Paper	5
Session 3 BedZED Case Study Handout	In Session 3	Paper	20
Session 3 Reflection Handout	In Session 3	Paper	5
Session 4			
Minute Paper	In Session 4	Paper	5
Session 4 Reflection Handout	In Session 4	Paper	5
Mini Project powerpoint	After Session 4	Online	35
Session 5			
Minute paper	In Session 5	Paper	5
Post Sustainability cmap	In Session 5	Online	20
Session 5 Reflection Handout	In Session 5	Paper	5
Module Reflection	TBD	TBD	5
Post Student Sustainability Survey	TBD	TBD	5
Other			
Student Curriculum Survey	TBD	TBD	5

Module Files and Workbook

The module files and workbooks are available for download at the following sites:

1. https://sites.google.com/site/marykatewatson/files/Capstone1.zip?attredirects=0&d=1
2. https://sites.google.com/site/marykatewatson/files/Capstone2.zip?attredirects=0&d=1
3. https://sites.google.com/site/marykatewatson/files/Capstone3.zip?attredirects=0&d=1

Sustainability Module Session 1: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 4090: Capstone Design
Estimated # of students: 65-100

Module and Session Overview:

This session is the first in a series of five sessions that compose a module intended to guide senior civil and environmental engineering (CEE) students in learning about and applying sustainability concepts and principles during design. As part of this session, students will complete preliminary assessments to benchmark their starting sustainability knowledge. First, students will complete a 20-minute online survey to characterize their knowledge of, interest in, and previous experiences related to sustainability. In class, students will complete a concept mapping workshop and construct a concept map (cmap) on the focus question: What is sustainability? Students must submit the survey, a practice cmap, a sustainability cmap, and session reflections.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 1 onto course website.
2. Make copies of Session 1 Concept Mapping Handout
3. Make copies of Session 1 Reflection Handout
4. Remind students to bring laptops to class
5. Email online sustainability survey to class.

Short term:

1. Display powerpoint to introduce session 1.
2. Distribute Session 1 Concept Mapping Handout and Session 1 Reflection Handout.

Student Preparation:

1. Take online Student Sustainability Survey (URL tbd).
2. Download Cmap Tools onto laptop.
3. Review Session 1 Workbook to become familiar with Cmap Tools.
4. Bring laptops to class.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
60-100	Session 1 Concept Mapping Handouts
60 – 100	Session 2 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 1 Module Workbook	Located within ModuleWorkbook.pdf
Session 1 Concept Mapping Handout	Located within ModuleWorkbook.pdf
Session 1 Reflection Handout	Located within ModuleWorkbook.pdf
Concept Mapping Workshop	ConceptMappingWorkshop.ppt
Student Sustainability Survey	SustainabilitySurvey.docx

Module Goals:

The sustainability concept mapping assessment will help benchmark students' starting knowledge related to two module goals.

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Benchmarking sustainability knowledge using concept maps

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Describe concept maps and their components.	Knowledge
2. Develop concept maps using CmapTools	Synthesis
3. Summarize their sustainability knowledge through construction of a concept map.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
15	Class starts; “Minute” paper
15	Cmapping workshop led by instructor
5	Practice concept mapping
5	Examining practice concept maps
60	Student creation of sustainability cmaps
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 1 Discussion Handouts and Session 1Reflection Handouts. Set up introduction powerpoint.
15	Instructor leads “minute” paper exercise. In 15 minutes, students respond to the following prompt: Describe sustainability in your own words. Explain that future minute papers will truly be one minute.
15	Instructor introduces cmaps and demonstrates how to use Cmap Tools.
5	Students use Cmap Tools to complete a practice cmap on the focus question: “What are French fries?”
5	Instructor leads students in identifying propositions and cross links in their practice cmaps.
60 (max)	Students complete a cmap on the focus question: “What is sustainability?” Cmaps must be submitted on course website.
10	Students complete Session 1 Reflection Handout. Students submit their practice cmaps, sustainability cmaps, and reflections at the end of class.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Preliminary survey	5
Practice cmap	5
Sustainability cmap	20
Session 1 reflections	5

Sustainability Module Session 2: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 4090: Capstone Design
Estimated # of students: 65-100

Module and Session Overview:

This session is the second in a series of five sessions that compose a module intended to guide senior civil and environmental engineering (CEE) students in learning about and applying sustainability concepts and principles during design. During this session, students will learn sustainable development, as well as five sustainability themes: (1) economic sustainability, (2) environmental sustainability, (3) social sustainability, (4) sustainable engineering, and (5) sustainability assessment.

Before class, each student will review the sustainable development paradigm and become an expert on a sustainability theme. To review sustainable development, each student will read "The Tragedy of the Commons" and respond to a reflection prompt. To become an expert on one sustainability theme, each student will read primary literature, respond to a reflection prompt, and review a sustainability tutorial. Students will then use provided outlines to plan a lecture. Themes should be chosen to ensure that each member in each group selects a different theme.

In class, students will teach their group members about their sustainability themes. During peer lectures, other group members will record key points using provided outlines. After peer lectures, small groups will share comments with the entire class. Students should submit a minute paper, two reflection prompts, a Session 2 Activity Handout, and a Session 2 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 2 onto course website.
2. Upload primary readings onto course website (Table 1).
3. Create an online assignment for each reflection prompt (Table 1).
4. Make copies of Session 2 Activity Handout.
5. Make copies of Session 2 Reflection Handout.
6. Ensure that one person in each group has elected to become an "expert" on one of the four sustainability themes.

Short term:

1. Display powerpoint to introduce session 2.
2. Distribute Session 2 Activity Handout.
3. Distribute Session 2 Reflection Handout.

Table 1. Primary literature and reflection prompts for the four sustainability themes.

Sustainability Theme	Primary Literature[1]	Reflection Prompt
Sustainable Development	Hardin, G., The Tragedy of the Commons. *Science* **1968,** *162*, (3859), 1243-1248.	Can humans escape The Tragedy of the Commons?
Economic Sustainability	Costanza, R.; Daly, H. E.; Bartholomew, J. A., Goals, Agenda, and Policy Recommendations for Ecological Economics. In *Ecological Economics: The Science and Management of Sustainability*, Costanza, R., Ed. Columbia University Press: West Sussex, UK, 1991.	Why should engineers consider economic sustainability during the design process?
Environmental Sustainability	Vellinga, P.; de Groot, R.; Klein, R., An Ecologically Sustainable Biosphere. In *The Environment: Towards a Sustainable Future*, Policy, Kluwer Academic Publishers: Dordecht, The Netherlands, 1994, pgs. 317-320; 325-326; 329-338.	Why should engineers consider environmental sustainability during the design process?
Social Sustainability	Partridge, E., Social sustainability: A useful theoretical framework? In *Australasian Political Science Association Annual Conference*, Dunedin, New Zealand, 2005.	Why should engineers consider social sustainability during the design process?
Sustainable Design	Mihelcic, J. R.; Crittenden, J. C.; Small, M. J.; Shonnard, D. R.; Hokanson, D. R.; Zhang, Q.; Chen, H.; Sorby, S. A.; James, V. U.; Sutherland, J. W.; Schnoor, J. L., Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science & Technology* **2003,** *37*, (23), 5314-5324.	How can engineers promote sustainable development?
Sustainability Assessment	Pope, J.; Annandale, D.; Saunders, A. M., Conceptualising sustainability assessment. *Environmental Impact Assessment Review* **2004,** *24*, 595-616.	Why is sustainability assessment important to engineers?

Student Preparation:

1. Read "The Tragedy of the Commons."
2. Respond to the sustainable development reflection prompt on the course website.
3. Choose one of the five sustainability themes on which to become an "expert."
4. Complete assigned reading for sustainability theme.
5. Respond to assigned reflection prompt on course website.
6. Read the sustainability tutorial.
7. Prepare to lead a lecture on his or her sustainability theme.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
60 – 100	Session 2 Activity Handouts
60 – 100	Session 2 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 2 Module Workbook	Located within ModuleWorkbook.pdf
Session 2 Activity Handout	Located within ModuleWorkbook.pdf
Session 2 Reflection Handout	Located within ModuleWorkbook.pdf
Session 2 Introduction	SessionTwoIntroduction.ppt

Module Goals:

After participation in the complete sustainability module, students should be able to:

Session Addresses Goal?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Conceptualizing sustainability through peer discussions

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Defend how sustainable development can combat the Tragedy of the Commons.	Comprehension
2. Compare neoclassical economics and weak sustainability to ecological economics and strong sustainability.	Comprehension
3. Relate how the precautionary principle is supported by the formal definition of environmental sustainability.	Evaluation
4. Recommend how engineers can promote the six characteristics of a sustainable community	Evaluation
5. Consider how the 9 Principles of Sustainable Engineering can be used to facilitate sustainable design, even though interrelationships and tensions between sustainability dimensions can complicate the process.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
10	Class starts; Group Formation, distribute handouts; overview handout
15	Economic sustainability lecture
15	Environmental sustainability lecture
15	Social sustainability lecture
15	Sustainable engineering lecture
15	Sustainability assessment lecture
5	Instructor-led debriefing
5	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Min	Activity Description
10	Student organize themselves into their capstone groups and pick up Session 2 Activity Handout and Reflection Handout. Instructor briefly introduces the activity.
15	Economic sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Environmental sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Social sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Sustainable design expert leads lecture. Group members use lecture outline to record key concepts.
15	Sustainability assessment expert leads lecture. Group members use lecture outline to record key concepts.
5	Instructor de-briefs the large group using the prompt: "Why is it important for engineers to learn about sustainability?"
5	Students complete Session 2 Reflection Handout. Students submit both the reflection and Activity Handouts.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Sustainability reflection	5
Sustainability theme reflection	5
Session 2 Activity Handout	20
Session 2 Reflection Handout	5

Sustainability Module Session 3: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 4090: Capstone Design
Estimated # of students: 65-100

Module and Session Overview:

This session is the third in a series of five sessions that compose a module intended to guide senior civil and environmental engineering (CEE) students in learning about and applying sustainability concepts and principles during design. During this session, students will work in their capstone design groups to analyze a case study on the Beddington Zero Energy Development (BedZED), as well as two case studies of their choices. Before class, each student is expected to read the BedZED case study, which is provided on the course website, as well as one other case study from a provided database. In class, student groups answer a series of questions designed to aid them in identifying economic, environmental, and social impacts of development projects, as well as assessing the extent of application of the 9 Principles of Sustainable Engineering in real-world projects. Students should submit a minute paper, a Session 3 BedZED Case Study Handout, and a Session 3 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 3 onto course website.
2. Make copies of Session 3 BedZED Case Study Handout.
3. Make copies of Session 3 Reflection Handout.
4. Remind students to bring a copy of the case study to class (1 per group).

Short term:

1. Display powerpoint to introduce session 3.
2. Distribute Session 3 BedZED Case Study Handout and Session 3 Reflection Handout.

Student Preparation:

8. Review BedZED case study provided on course website.
9. Bring a copy of the case study to class (1 per group)

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
60 – 100	Session 3 BedZED Case Study Handouts
60 – 100	Session 3 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 3 Workbook	Located within ModuleWorkbook.pdf
Session 3 BedZED Case Study Handout	Located within ModuleWorkbook.pdf
Session 3 Reflection Handout	Located within ModuleWorkbook.docx
BedZED Case Study	BedZED_CaseStudy.pdf
Session 3 Introduction	Session3Introduction.ppt

Module Goals:

After participation in the complete sustainability module, students should be able to:

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
X	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
X	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Examining sustainable design through evaluation of a real-world project

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Recognize the objectives of a project as economic, environmental, or social.	Knowledge
2. Identify strategies for meeting project economic, environmental, and social objectives.	Analysis
3. Assess the extent to which the 9 Principles of Sustainable Engineering are incorporated into an existing project.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
5	Class starts; Minute paper
5	Session introduction by instructor
45	Group examination of BedZED case study and supplementary case studies.
10	De-briefing led by instructor
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 3 BedZED Case Study Handouts and Session 3 Reflection Handouts. Set up introduction powerpoint.
5	Instructor leads "minute" paper exercise. In 15 minutes, students respond to the following prompt: Provide one interesting fact that you learned about through examining the BedZED case study.
5	Instructor provides an overview of the session
45	Student groups discuss BedZED by completing the Session 3 BedZED Case Study handout. Each group chooses two case studies from the provided database to analyze using the provided handout.
10	Instructor de-briefs the group by asking for responses to Session 3 BedZED Case Study handout. Ends discussion with the prompt: "Did anyone learn about a strategy that can be applied to your own project?"
10	Students complete Session 3 Reflection Handout. Students submit their Session 3 BedZED Case Study Handout (1 per group) and their reflections (1 per student).

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Session 3 BedZED Case Study Handout	20
Session 3 Reflections Handout	5

Sustainability Module Session 4: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 4090: Capstone Design
Estimated # of students: 65-100

Module and Session Overview:

This session is the fourth in a series of five sessions that compose a module intended to guide senior civil and environmental engineering (CEE) students in learning about and applying sustainability concepts and principles during design. During this session, student groups will begin a preliminary sustainability analysis of their capstone projects. Students are expected to apply knowledge learned from sessions 1-3 in completion of this mini-project. Guidelines are provided to students, and final work should be presented in a powerpoint presentation. The group with the best sustainability analysis will receive a reward (tbd).

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 4 onto course website.
2. Make copies of Session 4 Mini Project Handout.
3. Make copies of Session 4 Reflection Handout.
4. Remind students to bring laptops to class (1 per group).

Short term:

1. Display powerpoint to introduce session 4.
2. Distribute Session 4 Mini Project Handout and Session 4 Reflection Handout.

Student Preparation:

1. Review mini-project description (in workbook) and brainstorm ideas.
2. Bring laptop to class (1 per group).

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
60-100	Session 4 Mini Project Handouts
60 – 100	Session 4 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 4 Mini Project Handout	Included in ModuleWorkbook.pdf
Session 4 Reflection Handout	Included in ModuleWorkbook.pdf
Session 4 Introduction	SessionFourIntroduction.ppt

Module Goals:

After participation in the complete sustainability module, students should be able to:

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
X	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
X	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Integrating sustainability considerations into your capstone design project.

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Analyze their capstone design project from a systems perspective.	Analysis
2. Consider strategies for adhering to each of the 16 sustainable design criteria, which are based on the 9 Principles of Sustainable Engineering.	Evaluation
3. Construct a design abacus to identify the design alternative's strengths and weakness related to sustainability.	Synthesis

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
5	Class starts; Minute paper
5	Session introduction by instructor
120 (max)	Student completion of mini project
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 4 Mini Project Handouts and Session 4Reflection Handouts. Set up introduction powerpoint.
5	Instructor leads minute paper exercise. In one minute, students respond to the following prompt: Provide one example of how sustainability can be integrated into your capstone project.
5	Instructor introduces mini project.
120 (max)	Students use mini project description and information from sessions 2 and 3 to complete final powerpoint.
10	Students complete Session 4 Reflection Handout. Students will have one week after session to submit final powerpoint on course website.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Mini project powerpoint	35
Session 4 Reflection Handout	5

Sustainability Module Session 5: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 4090: Capstone Design
Estimated # of students: 65-100

Module and Session Overview:

This session is the last in a series of five sessions that compose a module intended to guide senior civil and environmental engineering (CEE) students in learning about and applying sustainability concepts and principles during design. During this session, students will complete post assessments to gauge what they have learned by participating in the module. First, before class, students will complete a 10-minute online survey to characterize their knowledge of, interest in, and previous experiences related to sustainability. In class, students will complete an abbreviated concept mapping workshop and construct a concept map (cmap) on the focus question: What is sustainability? Students must submit the before-class survey, a sustainability cmap, and Session 5 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 5 onto course website.
2. Make copies of Session 5 Concept Mapping Handout
3. Make copies of Module Evaluation Survey.
4. Remind students to bring laptops to class
5. Email online sustainability survey to class.

Short term:

1. Display powerpoint to introduce session 5.
2. Distribute Session 5 Concept Mapping Handout and Module Evaluation Survey.

Student Preparation:

1. Review Session 1 Workbook to become re-familiar with map Tools.
2. Review all module materials.
3. Bring laptops to class.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
60-100	Session 5 Concept Mapping Handouts
60 – 100	Module Evaluation Surveys
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 5 Workbook	Included in ModuleWorkbook.pdf
Session 5 Concept Mapping Handout	Included in ModuleWorkbook.pdf
Session 5 Reflection Handout	Included in ModuleWorkbook.pdf
Abbreviated Concept Mapping Workshop	AbbreviatedConceptMappingWorkshop.ppt
Post Student Sustainability Survey	PostSustainabilitySurvey.docx

Module Goals:

The sustainability concept mapping assessment will help benchmark students' sustainability knowledge related to two module goals.

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
A[1]	3. Analyze the impacts of a project on the economic, environmental, and social systems[1].	Analysis
A[1]	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design[1].	Evaluation

[1]Assessed through evaluation of final capstone projects.

Lesson Topic:

Showcasing Sustainability Knowledge using Concept Maps

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Define concept maps.	Knowledge
2. Develop concept maps using Cmap Tools	Synthesis
3. Summarize their sustainability knowledge through construction of a concept map.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
5	Class starts; “Minute” paper
15	Abbreviated cmapping workshop led by instructor
5	Student construction of sustainability concept maps
20	Session 5 reflection and module evaluation

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 5 Discussion Handouts and Session 5Reflection Handouts. Set up introduction powerpoint.
5	Instructor leads “minute” paper exercise. In 1 minute, students answer the questions: What was your favorite part about the module? Least favorite?
10	Instructor recaps use and construction of cmaps. Instructor reminds students that the extent to which they address the 16 Sustainable Design Criteria will be formally assessed in their final project reports.
60 (max)	Students complete a cmap on the focus question: “What is sustainability?” Cmaps must be submitted on course website.
10	Students complete and submit Session 5 Reflection Handout and Module Students also submit their sustainability cmaps.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Sustainability cmap	20
Session 5 Reflection Handout	5

APPENDIX I

SUSTAINABILITY MODULE FOR CORNERSTONE DESIGN COURSE

A five-part sustainability module was implemented into two sections of the Fall 2012 Civil Engineering Systems course. Using insights gained from assessments of the CEE curriculum and student sustainability knowledge, the module was originally developed for capstone design students. However, feedback from seniors indicated that they felt the module would be more beneficial in cornerstone design. Seniors also suggested that Session 2, where they learned about sustainability concepts through peer-lectures, should be less structured to allow for more group discussions. To determine whether peer-lectures or peer-discussions would best enhance students learning, Sections A and B of cornerstone design participated in the sustainability module with peer lectures and peer discussions, respectively. The instructor guide for implementing the cornerstone design version of the sustainability module is included below.

LEARNING ABOUT AND APPLYING SUSTAINABILITY CONCEPTS AND PRINCIPLES IN DESIGN:

Instructor Guide

Fall 2012

Introduction to the Sustainability Module

Research Study

A research study is being conducted to determine the effects of Civil and Environmental Engineering (CEE) curricula at Georgia Tech on student ability to apply sustainability concepts during engineering design. Students enrolled in CEE 300 will be asked to participate in a sustainability module designed to teach them about several sustainability topics that are pertinent to engineers. Several of the assignments completed during this module will be analyzed for research purposes, but no identifying information about students (i.e. name) will ever be disclosed. While module assignments are a required part of CEE 3000 and will be counted toward the final grade, student participation in this research study is voluntary. This means that students may elect to not have their assignments used in the research study. Students should contact Mary Katherine Watson (mwatson8@mail.gatech.edu) if they do not want to participate in this study.

Importance of Sustainability in Engineering

Although technological innovation may have contributed to current unsustainable practices, engineering is important for developing and implementing sustainable development strategies. In fact, most critical decisions related to sustainability, such as cost, appearance, materials selection, innovation, performance, environmental impact, and perceptions of quality, are made during the design process. As engineering students, CEE 3000 students must be ready to integrate sustainability considerations during design. After all, they will be making the decisions that will impact the sustainability of our future infrastructure.

Module Overview

The goal of this module is to guide students in learning about and applying sustainability concepts and principles during design. Completing these activities will not only help them to learn about sustainability, but will also help them complete their final projects. During the module, capstone groups will self-navigate through several before-class and in-class activities to learn about sustainability and sustainable design. All materials needed for this module are found in the Sustainability Module Workbook and the course website. Two options are available for Session 2. Students may either participate in group lectures or discussions (lesson plans provided for both formats). The module includes five class sessions:

- Session 1: Benchmarking Sustainability Knowledge Using Concept Maps
- Session 2A: Conceptualizing Sustainability through Peer Lectures
- Session 2B: Conceptualizing Sustainability through Peer Discussions
- Session 3: Examining Sustainable Design by Evaluating a Real-World Project
- Session 4: Conducting Sustainability Analyses
- Session 5: Showcasing Sustainability Knowledge Using Concept Maps

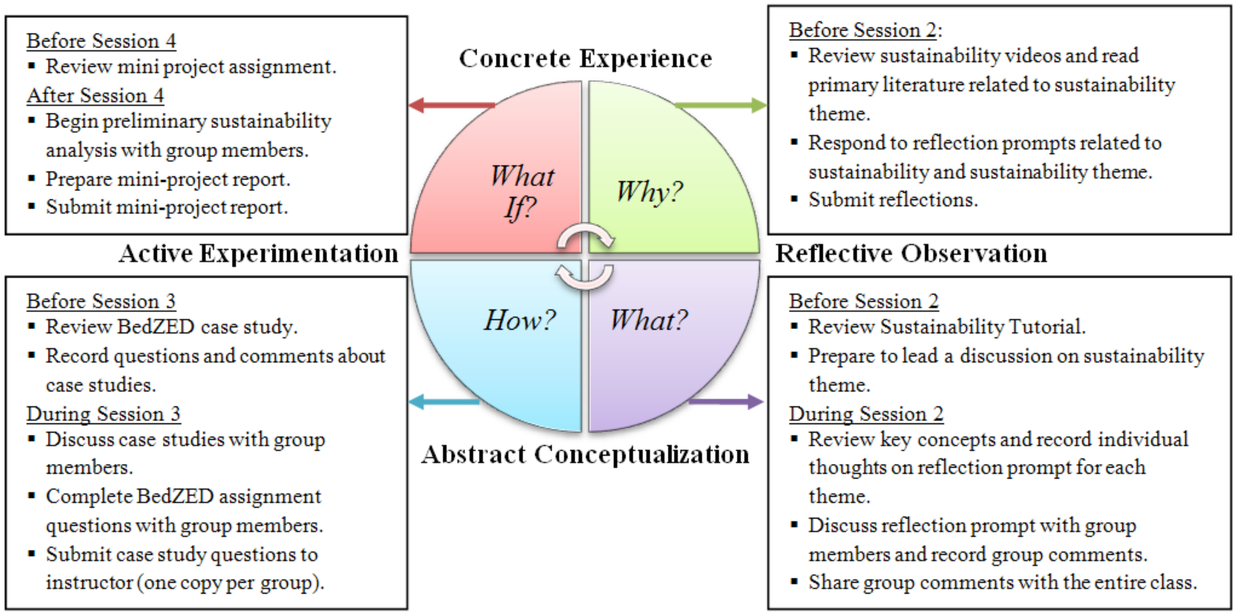
Module Learning Objectives

After completion of this five-part sustainability module, each student should be able to:

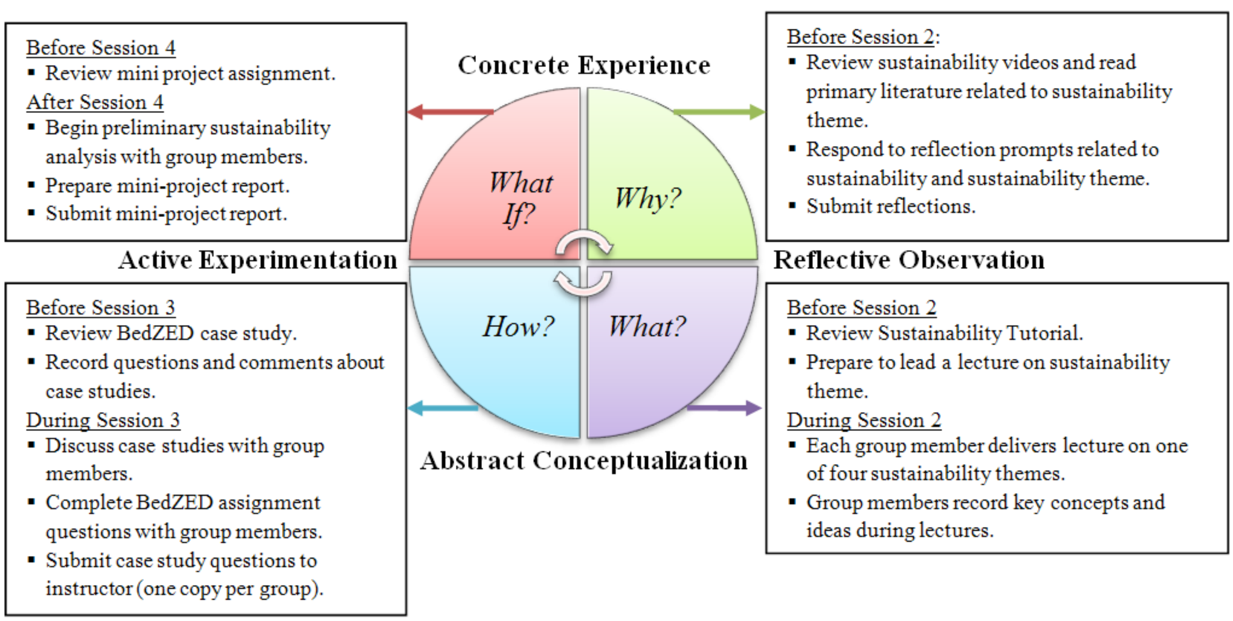
1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.
2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.
3. Analyze the impacts of a project on the economic, environmental, and social systems.
4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.

Module Design

This sustainability module is intentionally designed to improve student knowledge and application of sustainability by guiding them through a complete learning cycle. It is believed that complete learning occurs when students engage in all phases of the learning cycle, which includes concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE). Learning begins when a student engages in a given experience (CE) and continues as he or she reflects on that experience (RO). Student reflection leads to development of logical conclusions, to which theoretical or expert ideas can be added (AC). Finally, students test new concepts and skills (AE) to serve as templates for new experiences (CE). Each of the sessions was carefully developed to encourage students to complete each phase of the learning cycle.



Sequence of class activities based on learning cycle (discussion style for Session 2).



Sequence of class activities based on learning cycle (lecture style for Session 2).

Session Layout

To help ensure that the module goes smoothly, each session will be organized in the same manner.

6. At the beginning of class, the instructor will briefly review the activity. Students may be asked to complete "minute" papers (require slightly longer than one minute).
7. The instructor will provide a brief overview of the session.
8. Students will complete the major activity for the session. All activities will be completed in capstone design groups, with the exceptions of sessions 1 and 5.
9. Students will complete an exercise to reflect on the session.
10. Students will submit in class assignments to the instructor or online.

Time Requirements

Students are responsible for completing assignments both before and during each module class. Most before-class exercises will be completed individually, while most in-class assignments will be completed in capstone project groups. It is important that students complete before-class assignments because they help their groups to complete in-class assignments. Before-class and in-class exercises are expected to take 3.5 and 9 hours to complete, respectively. It is critical that students use the time provided in class so that module activities do not become overwhelming.

Session No.	Class Description	Time Required Before Class* (hr)	Time Required During Class* (hr)
1	Concept Mapping	0.5	1
2	Student-Led Sustainability Discussions	1.5	3
3	Sustainability Case Study	1	2
4	Sustainability Mini Project	0.5	3

*Estimated.

Grading

Students will earn an overall grade for completion of module activities that will be included in their final class grade. A summary of all assignments and associated points is provided below.

Assignment	Due Date	Submission	Points
Session 1: Concept Mapping			
Preliminary Student Sustainability Survey	Before Session 1	Online	5
Minute paper	In Session 1	Paper	5
Practice cmap	In Session 1	Online	5
Sustainability cmap	In Session 1	Online	25
Session 1 Reflection Handout	In Session 1	Paper	5
Session 2			
Sustainability reflection	Before Session 2	Online	5
Sustainability theme reflection	Before Session 2	Online	5
Session 2 Activity Handout	In Session 2	Paper	20
Session 2 Reflection Handout	In Session 2	Paper	5
Session 3			
Session 3 BedZED Case Study Handout	In Session 3	Paper	20
Session 3 Reflection Handout	In Session 3	Paper	5
Session 4			
Session 4 Reflection Handout	In Session 4	Paper	5
Mini Project report	After Session 4	Online	45
Session 5			
Minute paper	In Session 5	Paper	5
Post Sustainability cmap	In Session 5	Online	25
Session 5 Reflection Handout	In Session 5	Paper	5
Module Reflection Handout	In Session 5	Paper	5
Post Student Sustainability Survey	TBD	TBD	5

Module Files and Workbook

You can download a copy of all module materials at:

https://sites.google.com/site/marykatewatson/files/Sustainability%20Module%20for%20Civil%20Engineering%20Systems.zip?attredirects=0&d=1

Sustainability Module Session 1: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the first in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. As part of this session, students will complete preliminary assessments to benchmark their starting sustainability knowledge. If not completed on the first day of class, students will complete a 20-minute online survey to characterize their knowledge of, interest in, and previous experiences related to sustainability. In class, students will complete a concept mapping workshop and construct a concept map (cmap) on the focus question: What is sustainability? Students must submit the survey, a practice cmap, a sustainability cmap, and session reflections.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 1 onto course website.
2. Make copies of Session 1 Concept Mapping Handout
3. Make copies of Session 1 Reflection Handout
4. Remind students to bring laptops to class
5. Email online sustainability survey to class.

Short term:

1. Display powerpoint to introduce session 1.
2. Distribute Session 1 Concept Mapping Handout and Session 1 Reflection Handout.

Student Preparation:

1. Take online Student Sustainability Survey (URL tbd) *if* not given on the first day of class.
2. Download Cmap Tools onto laptop.
3. Review Session 1 Workbook to become familiar with Cmap Tools.
4. Bring laptops to class.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 1 Concept Mapping Handouts
40-65	Session 2 Reflection Handouts
1	Projector, screen, laptop

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 1 Module Workbook	Located within ModuleWorkbook.pdf
Session 1 Concept Mapping Handout	Session 1 Concept Mapping Handout.docx
Session 1 Reflection Handout	Session 1 Reflection Handout.docx
Concept Mapping Workshop	ConceptMappingWorkshop.ppt
Student Sustainability Survey	SustainabilitySurvey.docx

Module Goals:

The sustainability concept mapping assessment will help benchmark students' starting knowledge related to two module goals.

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Benchmarking sustainability knowledge using concept maps

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Describe concept maps and their components.	Knowledge
2. Develop concept maps using CmapTools	Synthesis
3. Summarize their sustainability knowledge through construction of a concept map.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
10	Class starts; “Minute” paper
15	Cmapping workshop led by instructor
5	Practice concept mapping
5	Examining practice concept maps
35	Student creation of sustainability cmaps
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 1 Discussion Handouts and Session 1Reflection Handouts. Set up introduction powerpoint.
10	Instructor leads “minute” paper exercise. In 15 minutes, students respond to the following prompt: Describe sustainability in your own words.
15	Instructor introduces cmaps and demonstrates how to use Cmap Tools.
5	Students use Cmap Tools to complete a practice cmap on the focus question: “What are French fries?”
5	Instructor leads students in identifying propositions and cross links in their practice cmaps.
35	Students complete a cmap on the focus question: “What is sustainability?” Cmaps must be submitted on course website.
10	Students complete Session 1 Reflection Handout. Students submit their practice cmaps, sustainability cmaps, and reflections at the end of class.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Preliminary survey	5
Practice cmap	5
Sustainability cmap	25
Session 1 reflections	5

Sustainability Module Session 2: A Lesson Plan (Discussion Version)

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the second in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. During this session, students will learn sustainable development, as well as four sustainability themes: (1) economic sustainability, (2) environmental sustainability, (3) social sustainability, and (4) sustainable engineering.

Before class, each student will review the sustainable development paradigm and become an expert on one sustainability theme. To become familiar with sustainable development, each student will watch two short videos and respond to a reflection prompt. To become an expert on one sustainability theme, each student will read primary literature, respond to a reflection prompt, and review a sustainability tutorial. Themes should be chosen to ensure that each member in each four-member group selects a different theme. Two students in a group of five may choose the same theme.

In class, group members first individually review the three key points highlighted on the Session 2 Activity Handout and record their thoughts on the corresponding discussion prompt. Afterwards, the expert leads a group discussion on the reflection prompt and may bring in information from their primary reading related to the theme. During discussions, each group member should record group discussion highlights. After each discussion, small groups will share comments with the entire class. Students should submit two reflection prompts, a Session 2 Activity Handout, and a Session 2 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 2 onto course website.
2. Upload primary readings onto course website (Table 1).
3. Create an online assignment for each reflection prompt (Table 1).
4. Make copies of Session 2 Activity Handout.
5. Make copies of Session 2 Reflection Handout.
6. Ensure that one person in each group has elected to become an "expert" on one of the four sustainability themes.

Short term:

1. Organize students into project groups.
2. Distribute Session 2 Activity Handout.
3. Distribute Session 2 Reflection Handout.

Table 1. Primary literature and reflection prompts for the four sustainability themes.

Sustainability Theme	Primary Literature[1]	Reflection Prompt
Economic Sustainability	Costanza, R.; Daly, H. E.; Bartholomew, J. A., Goals, Agenda, and Policy Recommendations for Ecological Economics. In *Ecological Economics: The Science and Management of Sustainability*, Costanza, R., Ed. Columbia University Press: West Sussex, UK, 1991.	Defend why you are a proponent of either weak or strong sustainability.
Environmental Sustainability	Vellinga, P.; de Groot, R.; Klein, R., An Ecologically Sustainable Biosphere. In *The Environment: Towards a Sustainable Future*, Policy, Kluwer Academic Publishers: Dordecht, The Netherlands, 1994, pgs. 317-320; 325-326; 329-338.	Relate how the application of the precautionary principle may support environmental sustainability. You can also defend your opposition to the precautionary principle.
Social Sustainability	Partridge, E., Social sustainability: A useful theoretical framework? In *Australasian Political Science Association Annual Conference*, Dunedin, New Zealand, 2005.	Recommend how engineers can promote the six characteristics of a socially sustainable community.
Sustainable Design	Mihelcic, J. R.; Crittenden, J. C.; Small, M. J.; Shonnard, D. R.; Hokanson, D. R.; Zhang, Q.; Chen, H.; Sorby, S. A.; James, V. U.; Sutherland, J. W.; Schnoor, J. L., Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science & Technology* **2003,** *37*, (23), 5314-5324.	Describe how the interrelations and tensions between the three sustainability dimensions can complicate sustainable design. How can adhering the 9 principles of sustainable design facilitate sustainable design?

Student Preparation:

1. Watch the two sustainability-related videos.
2. Respond to the sustainable development reflection prompt on the course website.
3. Choose one of the four sustainability themes on which to become an "expert."
4. Complete assigned reading for sustainability theme.
5. Respond to assigned reflection prompt on course website for that theme.
6. Read the sustainability tutorial.
7. Prepare to lead a group discussion on his or her sustainability theme reflection prompt.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 2 Activity Handouts
40-65	Session 2 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 2 Module Workbook	Located within ModuleWorkbook.pdf
Session 2 Activity Handout	Located within ModuleWorkbook.pdf
Session 2 Reflection Handout	Session 2 Reflection Handout.docx

Module Goals:

After participation in the complete sustainability module, students should be able to:

Session Addresses Goal?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Conceptualizing sustainability through peer discussions

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Defend how sustainable development can combat the Tragedy of the Commons.	Comprehension
2. Compare neoclassical economics and weak sustainability to ecological economics and strong sustainability.	Comprehension
3. Relate how the precautionary principle is supported by the formal definition of environmental sustainability.	Evaluation
4. Recommend how engineers can promote the six characteristics of a sustainable community	Evaluation
5. Consider how the 9 Principles of Sustainable Engineering can be used to facilitate sustainable design, even though interrelationships and tensions between sustainability dimensions can complicate the process.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
10	Class starts; Group Formation, distribute handouts; Overview lecture
15	Economic sustainability discussion
15	Environmental sustainability discussion
15	Social sustainability discussion
15	Sustainable engineering discussion
10	Instructor-led debriefing; Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
10	Student organize themselves into their capstone groups and pick up Session 2 Activity Handout and Reflection Handout. Instructor introduces activity.
2	*Think*: Each student reviews economic sustainability key points on Session 2 Activity Handout and records thoughts on related discussion question.
10	*Group*: Economic sustainability expert leads group discussion, while group (including leading expert) records key points.
3	*Share*: Instructor recaps economic sustainability discussions by calling on at least one group to share comments.
2	*Think*: Each student reviews environmental sustainability key points on Session 2 Activity Handout and records thoughts on discussion question.
10	*Group*: Environmental sustainability expert leads group discussion, while group (including leading expert) records key points.
3	*Share*: Instructor recaps environmental sustainability discussions by calling on at least one group to share comments.
2	*Think*: Each student reviews social sustainability key points on Session 2 Activity Handout and records thoughts on discussion question.
10	*Group*: Social sustainability expert leads group discussion, while group (including leading expert) records key points.
3	*Share*: Instructor recaps social sustainability discussions by calling on at least one group to share comments.
2	*Think*: Each student reviews sustainable engineering key points on Session 2 Activity Handout and records thoughts on related discussion question.
10	*Group*: Sustainable engineering expert leads group discussion, while group (including leading expert) records key points.
3	*Share*: Instructor recaps sustainable engineering discussions.
5	Instructor de-briefs the large group using the prompt: "Why is it important for engineers to learn about sustainability?"
5	Students complete Session 2 Reflection Handout. Students submit handouts.

Student Deliverables

Deliverable	Potential Points
Sustainability reflection	5
Sustainability theme reflection	5
Session 2 Activity Handout	20
Session 2 Reflection Handout	5

Sustainability Module Session 2: A Lesson Plan (Lecture Version)

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the second in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. During this session, students will learn sustainable development, as well as four sustainability themes: (1) economic sustainability, (2) environmental sustainability, (3) social sustainability, and (4) sustainable engineering.

Before class, each student will review the sustainable development paradigm and become an expert on one sustainability theme. To become familiar with sustainable development, each student will watch two short videos and respond to a reflection prompt. To become an expert on one sustainability theme, each student will read primary literature, respond to a reflection prompt, and review a sustainability tutorial. Themes should be chosen to ensure that each member in each four-member group selects a different theme. Two students in a group of five may choose the same theme.

In class, each "expert" will teach group members about his or her theme through a 15 minute lecture. During each lecture, group members not presenting should use the following lecture outlines to record key concepts and ideas. Students should submit two reflection prompts, a Session 2 Activity Handout, and a Session 2 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 2 onto course website.
2. Upload primary readings onto course website.
3. Create an online assignment for each reflection prompt.
4. Make copies of Session 2 Activity Handout.
5. Make copies of Session 2 Reflection Handout.
6. Ensure that one person in each group has elected to become an "expert" on one of the four sustainability themes.

Short term:

1. Organize students into project groups.
2. Distribute Session 2 Activity Handout.
3. Distribute Session 2 Reflection Handout.

Sustainability Theme	Primary Literature[1]	Reflection Prompt
Economic Sustainability	Costanza, R.; Daly, H. E.; Bartholomew, J. A., Goals, Agenda, and Policy Recommendations for Ecological Economics. In *Ecological Economics: The Science and Management of Sustainability*, Costanza, R., Ed. Columbia University Press: West Sussex, UK, 1991.	Defend why you are a proponent of either weak or strong sustainability.
Environmental Sustainability	Vellinga, P.; de Groot, R.; Klein, R., An Ecologically Sustainable Biosphere. In *The Environment: Towards a Sustainable Future*, Policy, Kluwer Academic Publishers: Dordecht, The Netherlands, 1994, pgs. 317-320; 325-326; 329-338.	Relate how the application of the precautionary principle may support environmental sustainability. You can also defend your opposition to the precautionary principle.
Social Sustainability	Partridge, E., Social sustainability: A useful theoretical framework? In *Australasian Political Science Association Annual Conference*, Dunedin, New Zealand, 2005.	Recommend how engineers can promote the six characteristics of a socially sustainable community.
Sustainable Design	Mihelcic, J. R.; Crittenden, J. C.; Small, M. J.; Shonnard, D. R.; Hokanson, D. R.; Zhang, Q.; Chen, H.; Sorby, S. A.; James, V. U.; Sutherland, J. W.; Schnoor, J. L., Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science & Technology* **2003,** *37*, (23), 5314-5324.	Describe how the interrelations and tensions between the three sustainability dimensions can complicate sustainable design. How can adhering the 9 principles of sustainable design facilitate sustainable design?

Student Preparation:

Before class, each student will review the sustainable development paradigm by completing the following activities:

1. Watch a short video on the Tragedy of the Commons (http://www.youtube.com/watch?v=MLirNeu-A8I).
2. Watch a short video on sustainable development (http://www.youtube.com/watch?v=Oa5dPsjrkik).
3. Respond to the reflection prompt: Defend why you support or reject the notion that humans can escape the Tragedy of the Commons. Submit responses on Tsquare.

Before class, each student will become an "expert" on one of four sustainability themes by completing the following activities:

1. Choose one sustainability theme: economic sustainability, environmental sustainability, social sustainability, or sustainable design. Each group member should choose a different theme, unless group has more than four members.
2. Each student reads the primary literature related to his or her sustainability theme (Table 1).
3. Each student responds to the reflection prompt for his or her sustainability theme (Table 1). Submit responses on Tsquare.
4. Each student reviews the *entire* Sustainability Tutorial located in the Session 2 Workbook.
5. Each student consults the "Suggested Readings" at the end of the Sustainability Tutorial if he or she needs additional information on your sustainability theme.
6. Each student prepares a 10-12 minute lecture using the lecture outline for his or her theme.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 2 Activity Handouts
40-65	Session 2 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 2 Module Workbook	Located within ModuleWorkbook.pdf
Session 2 Activity Handout	Located within ModuleWorkbook.pdf
Session 2 Reflection Handout	Session 2 Reflection Handout.docx

Module Goals:

After participation in the complete sustainability module, students should be able to:

Session Addresses Goal?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Conceptualizing sustainability through peer discussions

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Defend how sustainable development can combat the Tragedy of the Commons.	Comprehension
2. Compare neoclassical economics and weak sustainability to ecological economics and strong sustainability.	Comprehension
3. Relate how the precautionary principle is supported by the formal definition of environmental sustainability.	Evaluation
4. Recommend how engineers can promote the six characteristics of a sustainable community	Evaluation
5. Consider how the 9 Principles of Sustainable Engineering can be used to facilitate sustainable design, even though interrelationships and tensions between sustainability dimensions can complicate the process.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
10	Class starts; Group Formation, distribute handouts; overview handout
15	Economic sustainability lecture
15	Environmental sustainability lecture
15	Social sustainability lecture
15	Sustainable engineering lecture
5	Instructor-led debriefing
5	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
10	Student organize themselves into their capstone groups and pick up Session 2 Activity Handout and Reflection Handout. Instructor briefly introduces the activity.
15	Economic sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Environmental sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Social sustainability expert leads lecture. Group members use lecture outline to record key concepts.
15	Sustainable design expert leads lecture. Group members use lecture outline to record key concepts.
5	Instructor de-briefs the large group using the prompt: "Why is it important for engineers to learn about sustainability?"
5	Students complete Session 2 Reflection Handout. Students submit both the reflection and Activity Handouts.

Student Deliverables

Deliverable	Potential Points
Sustainability reflection	5
Sustainability theme reflection	5
Session 2 Activity Handout	20
Session 2 Reflection Handout	5

Sustainability Module Session 3: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the third in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. During this session, students will work in their project groups to analyze a case study on the Beddington Zero Energy Development (BedZED). Before class, each student is expected to read the case study, which is provided on the course website. In class, the instructor reviews systems analysis and examples of civil engineering systems to help students with this activity. Afterward, student groups answer a series of questions designed to aid them in identifying economic, environmental, and social impacts of development projects, as well as assessing the extent of application of the 9 Principles of Sustainable Engineering in a real-world project. Students should submit a minute paper, a Session 3 BedZED Case Study Handout, and a Session 3 Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 3 onto course website.
2. Upload Civil Engineering Systems powerpoint.
3. Make copies of Session 3 BedZED Case Study Handout.
4. Make copies of Session 3 Reflection Handout.
5. Remind students to bring a copy of the case study to class (1 per group).

Short term:

1. Distribute Session 3 BedZED Case Study Handout
2. Distribute Session 3 Reflection Handout.

Student Preparation:

1. Review BedZED case study provided on course website.
2. Bring a copy of the case study to class (1 per group)

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 3 BedZED Case Study Handouts
40-65	Session 3 Reflection Handouts
1	Projector, screen, laptop

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 3 Workbook	Located within ModuleWorkbook.pdf
Session 3 BedZED Case Study Handout	Located within ModuleWorkbook.pdf
Session 3 Reflection Handout	Session 3 Reflection Handout.docx
BedZED Case Study	BedZED_CaseStudy.pdf
Examples of Civil Engineering Systems	CivilEngineeringSystems.ppt

Module Goals:

After participation in the complete sustainability module, students should be able to:

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
X	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
X	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Examining sustainable design through evaluation of a real-world project

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Recognize the objectives of a project as economic, environmental, or social.	Knowledge
2. Identify strategies for meeting project economic, environmental, and social objectives.	Analysis
3. Assess the extent to which the 9 Principles of Sustainable Engineering are incorporated into an existing project.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
5	Organize into groups, introduce activities.
15	Review of systems analysis.
45	Group examination of BedZED case study
5	De-briefing led by instructor
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 3 BedZED Case Study Handouts and Session 3 Reflection Handouts. Set up introduction powerpoint.
5	Organize students into groups and introduce activities.
15	Instructor provides a brief review of systems analysis, with specific examples for civil engineering systems (using ppt).
45	Student groups discuss BedZED by completing the Session 3 BedZED Case Study handout.
5	Instructor de-briefs the group by asking for responses to Session 3 BedZED Case Study handout.
10	Students complete Session 3 Reflection Handout. Students submit their Session 3 BedZED Case Study Handout (1 per group) and their reflections (1 per student).

Student Deliverables

Deliverable	Potential Points
Session 3 BedZED Case Study Handout	20
Session 3 Reflections Handout	5

Sustainability Module Session 4: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the fourth in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. During this session, student groups will begin a preliminary sustainability analysis based on their project. Students are expected to apply knowledge learned from sessions 1-3 in completion of this mini-project. Guidelines are provided to students, and final work should be presented in a document on Tsquare. The group with the best sustainability analysis will receive a reward (tbd).

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 4 onto course website.
2. Make copies of Session 4 Mini Project Handout.
3. Make copies of Session 4 Reflection Handout.
4. Remind students to bring laptops to class (1 per group).

Short term:

1. Display powerpoint to introduce session 4.
2. Distribute Session 4 Mini Project Handout and Session 4 Reflection Handout.

Student Preparation:

1. Review mini-project description (in workbook) and brainstorm ideas.
2. Bring laptop to class (1 per group).

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 4 Mini Project Handouts
40-65	Session 3 Reflection Handouts
1	Projector, screen, laptop to display introductory powerpoint

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 4 Mini Project Handout	Located within ModuleWorkbook.pdf
Session 4 Reflection Handout	Session 4 Reflection Handout.docx
Session 4 Introduction	SessionFourIntroduction.ppt

Module Goals:

After participation in the complete sustainability module, students should be able to:

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
X	3. Analyze the impacts of a project on the economic, environmental, and social systems.	Analysis
X	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design.	Evaluation

Lesson Topic:

Conducting sustainability analyses

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Analyze an existing project from a systems perspective.	Analysis
2. Evaluate consideration of the 9 Principles of Sustainable Engineering, in existing projects.	Evaluation
3. Construct a design abacus to identify a design's strengths and weakness related to sustainability.	Synthesis

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
5	Class starts; Introduce activity
65	Student completion of mini project
10	Student reflections

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 4 Mini Project Handouts and Session 4Reflection Handouts.
5	Instructor reviews the mini-project and expectations for submission.
75	Students use mini project description and information from sessions 2 and 3 to complete final document.
10	Students complete Session 4 Reflection Handout. Students will have one week after session to submit final document on Tsquare.

Student Deliverables

Deliverable	Potential Points
Mini project document	45
Session 4 Reflection Handout	5

Sustainability Module Session 5: A Lesson Plan

Course Details:

Instructor: Mary Katherine Watson
Course Title: CEE 3000: Civil Engineering Systems
Estimated # of students: 40-65

Module and Session Overview:

This session is the last in a series of five sessions that compose a module intended to guide students in learning about and applying sustainability concepts and principles during design. During this session, students will complete post assessments to gauge what they have learned by participating in the module. Before class, students should review materials form the sustainability module. In class, students will complete an abbreviated concept mapping workshop and construct a concept map (cmap) on the focus question: What is sustainability? Students must submit their sustainability cmap, a Session 5 Reflection Handout, a Module Reflection Handout.

Room Configuration:

Ideal: Round tables for groups of five.

Expected: The classroom is a large lecture hall with long tables and attached seating. Students will be allowed to sit on the floor in groups or encouraged to use both sides of the tables so they can face group members.

Instructor Preparation:

Long term:

1. Upload workbook for session 5 onto course website.
2. Make copies of Session 5 Concept Mapping Handout.
3. Make copies of Session 5 Reflection Handout.
4. Make copies of Module Reflection Handout.
5. Remind students to bring laptops to class.

Short term:

1. Distribute Session 5 Concept Mapping Handout.
2. Distribute Session 5 Reflection Handout
3. Distribute Module Reflection Handout.

Student Preparation:

1. Review Session 1 Workbook to become re-familiar with map Tools.
2. Review all module materials.
3. Bring laptops to class.

Materials & Supplies:

Several items are required for session dissemination:

Quantity	Item
40-65	Session 5 Concept Mapping Handouts
40-65	Session 5 Reflection Handout
40-65	Module Reflection Handouts
1	Projector, screen, laptop

Associated Files:

Several files are required for session dissemination:

Quantity	Item
Sustainability Module Workbook	ModuleWorkbook.pdf
Session 5 Workbook	Included in ModuleWorkbook.pdf
Session 5 Concept Mapping Handout	Included in ModuleWorkbook.pdf
Session 5 Reflection Handout	Included in ModuleWorkbook.pdf
Module Reflection Handout	Included in ModuleWorkbook.pdf
Abbreviated Concept Mapping Workshop	AbbreviatedConceptMappingWorkshop.ppt

Module Goals:

The sustainability concept mapping assessment will help benchmark students' sustainability knowledge related to two module goals.

Goal Assessed?	Module Goals	Bloom's Taxonomy Level
X	1. Describe sustainability by using breadth and depth of knowledge related to the economic, environmental, social, and temporal aspects of sustainability.	Knowledge
X	2. Summarize the interconnected nature of the economic, environmental, social, and temporal aspects of sustainability.	Comprehension
	3. Analyze the impacts of a project on the economic, environmental, and social systems[1].	Analysis
	4. Assess how the 9 Principles of Sustainable Engineering can be applied during engineering design[1].	Evaluation

Lesson Topic:

Showcasing Sustainability Knowledge using Concept Maps

Session Learning Objectives:

After participation in this session, students will be able to:

Session Objectives	Bloom's Taxonomy Level
1. Define concept maps.	Knowledge
2. Develop concept maps using Cmap Tools	Synthesis
3. Summarize their sustainability knowledge through construction of a concept map.	Evaluation

Lesson Agenda

The session will include the following activities:

Duration (min.)	Name of Activity
5	Before class preparation
10	Class starts; “Minute” paper
5	Abbreviated cmapping workshop led by instructor
35	Student construction of sustainability concept maps
15	Student reflection on session and module.

Lesson Procedure

The session activities will be led through the following steps:

# of Minutes	Activity Description
5	Distribute Session 5 Discussion Handouts and Session 5Reflection Handouts. Set up introduction powerpoint.
10	Instructor leads “minute” paper exercise. In 1 minute, students respond to the prompt: Describe sustainability in your own words.
5	Instructor recaps use and construction of cmaps.
35	Students complete a cmap on the focus question: “What is sustainability?” Cmaps must be submitted on course website.
10	Students complete and submit Session 5 Module Reflection Handout, Module Reflection Handout, and their sustainability cmaps.

Student Deliverables

Deliverable	Potential Points
Minute paper	5
Sustainability cmap	25
Session 5 Reflection Handout	5
Module Reflection Handout	5

Note: Sustainability survey will be completed in a subsequent class (5 potential points).

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